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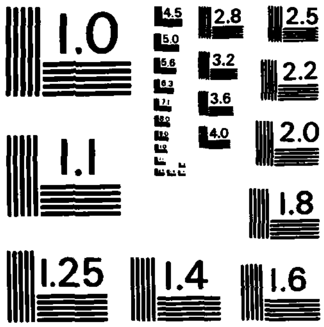

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ANALYTICAL AND DATA PROCESSING TECHNIQUES FOR INTERPRETATION OF GEOPHYSICAL SURVEY DATA WITH SPECIAL APPLICATION TO CAVITY DETECTION

by

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September 1982

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under Project No. 4A161102AT22, Task A0
Work Unit 002

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER Miscellaneous Paper GL-82-16	2. GOVT ACCESSION NO. AD-A121	3. RECIPIENT'S CATALOG NUMBER 196
4. TITLE (and Subtitle) ANALYTICAL AND DATA PROCESSING TECHNIQUES FOR INTERPRETATION OF GEOPHYSICAL SURVEY DATA WITH SPECIAL APPLICATION TO CAVITY DETECTION		5. TYPE OF REPORT & PERIOD COVERED Final report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Dwain K. Butler, Anthony F. Gangi, Ronald E. Wahl, Donald E. Yule, and Donald E. Barnes		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Geotechnical Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project 4A161102AT22 Task A0, Work Unit 002
11. CONTROLLING OFFICE NAME AND ADDRESS Office, Chief of Engineers, U. S. Army Washington, D. C. 20314		12. REPORT DATE September 1982 13. NUMBER OF PAGES 233
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22151.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cavity detection
Geophysical data interpretation
Geophysical data processing
Geophysical surveys
Gravimetric surveys
Resistivity surveys
Seismic surveys

are presented

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Presented ~~are~~ results of an effort directed toward the improvement of geophysical data acquisition, processing, and interpretation. Much of the discussion centers around the adaptation of existing or the development of new computer programs and their methodologies for processing and interpreting data acquired from electrical resistivity, microgravity, and seismic methods.

Three programs for processing and interpreting electrical resistivity are discussed: (a) RESDIR computes the apparent resistivity as a (Continued)

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20. ABSTRACT (Continued).

function of electrode spacing for a given model of vertical subsurface resistivity variations; (b) RESINV calculates the model of vertical subsurface resistivity variation given the apparent resistivities acquired in the field; and (c) RESDAT is a general purpose resistivity program which handles data acquired from horizontal profiling and vertical sounding surveys.

Three programs used in conjunction with microgravity surveys are documented: (a) TIDES computes the theoretical variation in gravity caused by earth tides at any location; (b) TALGRAD calculates gravity and gravity-gradient profiles across two-dimensional subsurface models; and (c) HILBERT computes the Hilbert transform which is used to determine the vertical velocity gradient. Two gravity methodologies presented describe: (a) a technique which reduces errors in microgravity surveying through use of optimal gravity station schemes, and (b) the use of polynomial surface fitting for determination of the required field component from a set of data.

Several computer programs for processing and interpretation of seismic refraction and crosshole survey data are documented. Four programs which digitize, process, and interpret analog seismic records are presented. These programs expedite the processing of this type of data. In addition, REFRDIR and REFRINV were developed to aid in data interpretation of refraction data. Changes which made an existing computer program, CROSSHOLE, an interactive time-sharing program are documented.

Recommendations are made toward achievement of higher goals aimed at automatic data processing and interpretation of geophysical data.

PREFACE

The study reported herein was performed during the period October 1978 to May 1982 under Department of the Army Project No. 4A161102AT22, "Research in Soil and Rock Mechanics," Task AO, Work Unit 002, "Analytical and Data Processing Techniques for Interpretation of Geophysical Properties."

The work was performed by Messrs. Dwain K. Butler, Ronald E. Wahl, and Donald E. Yule, Earthquake Engineering and Geophysics Division (EE&GD), Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss.; Mr. Donald E. Barnes, Geomechanics Division, Structures Laboratory, WES; and Dr. Anthony F. Gangi, Department of Geophysics, Texas A&M University, College Station, Tex., under the direct supervision of Dr. Arley G. Franklin, Chief, EE&GD, and the general supervision of Dr. William F. Marcuson III, Chief, GL. The work by Dr. Gangi was performed under Contract No. DACA39-79-M-0074 and involved preparing and documenting the computer programs REFRDIR and REFRINV. Mr. Wahl developed the computer programs SEISDIG, SEISPLOT, and REFINT. The computer program DOMER was written by Mr. Yule. Mr. Barnes developed the computer programs PLOT2 and PLOTLL and provided assistance in the use of these programs. This report was prepared by Mr. Butler.

The study was closely coordinated with work planned by Mr. Joseph R. Curro, Jr., Chief, Field Investigations Group, EE&GD, GL, under CWIS Work Unit 31150, "Remote Delineation of Cavities and Discontinuities in Rock," and by Mr. Butler under DA Project No. 4A161101A91D, "Assessment of Microgravimetry for Geotechnical Applications."

COL Tilford C. Creel, CE, was Commander and Director of WES during the conduct of this study. Mr. Fred R. Brown was Technical Director.

CONTENTS

Page

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
inches	2.54	centimetres
miles (U. S. statute)	1.609347	kilometres

ANALYTICAL AND DATA PROCESSING TECHNIQUES FOR INTERPRETATION OF GEOPHYSICAL SURVEY DATA WITH SPECIAL APPLICATION TO CAVITY DETECTION

PART I: INTRODUCTION

Background

1. In foundation investigations for permanent military facilities ranging from the common post facilities such as hospitals, barracks, etc., to underground command, control, and communication (C^3) facilities, there is a need for accurate information on subsurface stratigraphy, structure, and physical properties. Presently, this information is obtained through a combination of drilling, laboratory testing, and geophysical testing. Emphasis in the field investigation is on drilling and logging of borings which is a relatively expensive procedure. Often as much as five percent of the construction cost is expended in geotechnical investigations for military facilities and over half of this is spent in the field. Geophysical methods have the potential for reducing these costs; however, the full potential of geophysical methods to reduce the number of borings required is not presently being utilized partly because processing and interpretation of geophysical data in the U. S. Army Corps of Engineers usually is done manually. This has evolved primarily because judgment is required in the data reduction and interpretation process. The manual methods are very labor-intensive, and frequently there are considerable delays in reporting survey results due to processing "backlogs." Also, since hand methods are being used, recent developments in wave propagation and potential field theory, which involve large amounts of computation and could assist in the interpretation of data, are not being utilized.

Applications of Geophysical Methodology

2. The various types of surface and subsurface geophysical methods are reviewed in Engineer Manual 1110-1-1802 (Department of the

Army, 1979). This report will concentrate on three of the surface geophysical methods and one cross-borehole method:

a. Electrical resistivity.

b. Microgravimetry.

c. Seismic refraction.

d. Crosshole seismic method.

3. In addition to foundation investigations to aid in facility design and construction, geophysical methods are applicable to post-construction facility development functions, such as groundwater exploration, and monitoring functions, such as groundwater contamination detection and subsurface intrusion prevention and detection. Table 1 summarizes the applicability of the above four geophysical methods to various military facility design, construction, development, and monitoring functions.

Geophysical Data Sources

4. As described in the Preface, the work described here was closely coordinated with two other research efforts. In this way, efforts under the three projects were complementary, and relevant field data were available for processing and interpretation using techniques developed during the present work. Specifically, the field efforts involved the evaluation of some 28 geophysical techniques for cavity detection and delineation at two natural cavity test sites in Florida, and many of the examples used in this report are drawn from the data from these sites. Figure 1 is a location map showing the two sites. The Medford Cave site has a relatively shallow (<10 m) air-filled cavity system; Figure 2 shows a plan view of the known cave system and the geophysical survey area at the site. The Manatee Springs site has a deeper ($\sim$30 m) water-filled cavity system; Figure 3 is a plan map of the known cavity system and the area used for the geophysical surveys. Cavity detection and delineation is considered a particularly appropriate application since the presence of cavities, either natural (e.g., solution cavities in carbonates) or man-made (abondoned mine workings or

Table 1

Applicability of Geophysical Methods

Use of Method	Geophysical Method			
	Seismic Refraction	Seismic Crosshole	Electrical Resistivity	Microgravity
Site selection	1	4	1	1
Stratigraphy and lithology definition	1	1	1	3
Depth to top of rock	1	4,5	1,2	1,2
Geologic structure determination	1,2	2,3	1,2	1
Groundwater exploration and assessment	1	4,5	1	1,2
Groundwater contamination detection	5	5	1	5
Construction materials exploration (sand and gravel)	2	4,5	1	2
Facility monitoring/perimeter integrity	3,4	4	1	1

NOTE:
1 - Primary usefulness
2 - Secondary usefulness
3 - Has indirect or limited usefulness
4 - Could be used but not best or practical approach
5 - Not applicable
2,3 - Indicates a range of 2 to 3, or that applicability may vary depending on circumstances

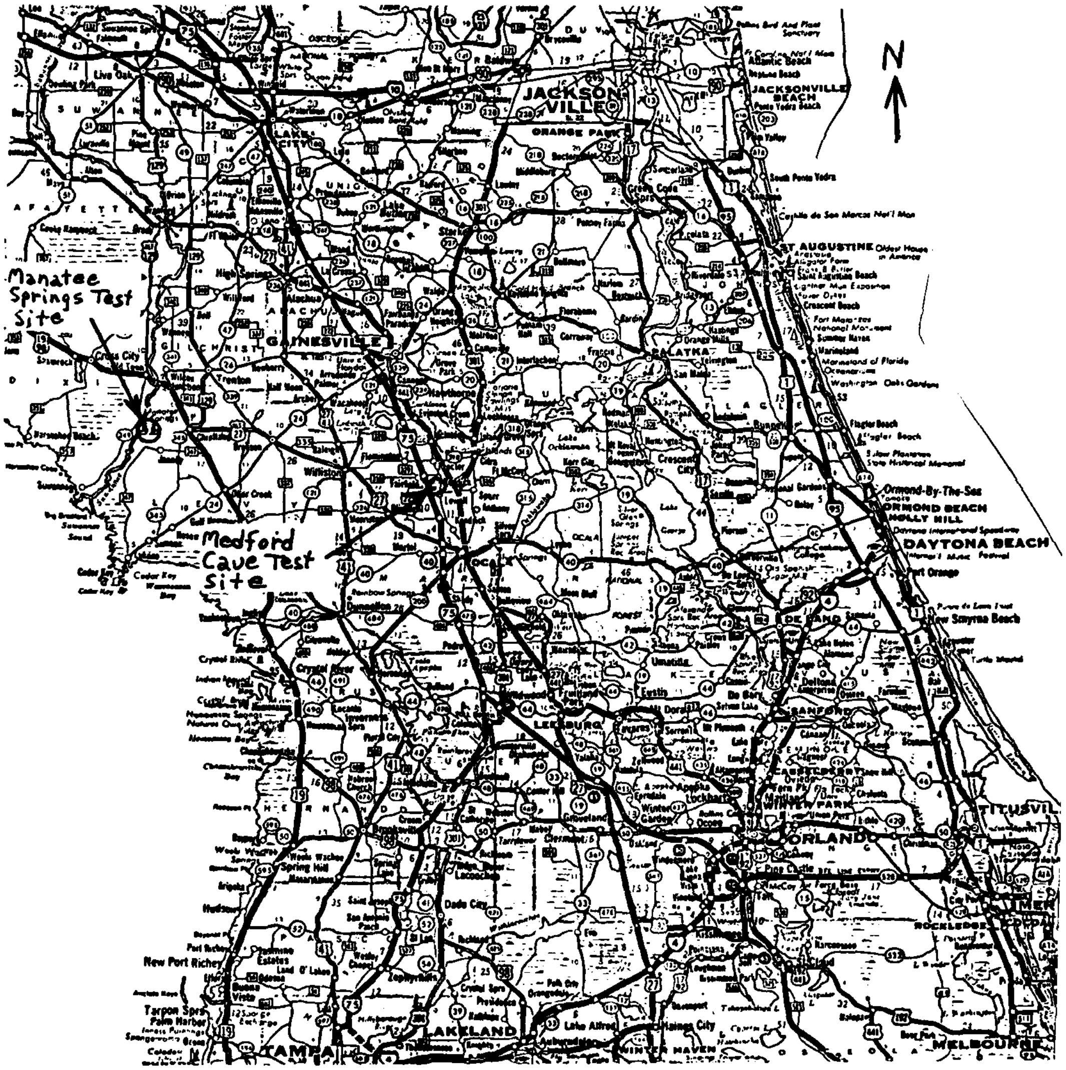


Figure 1. Map showing locations of Medford Cave and Manatee Springs test sites

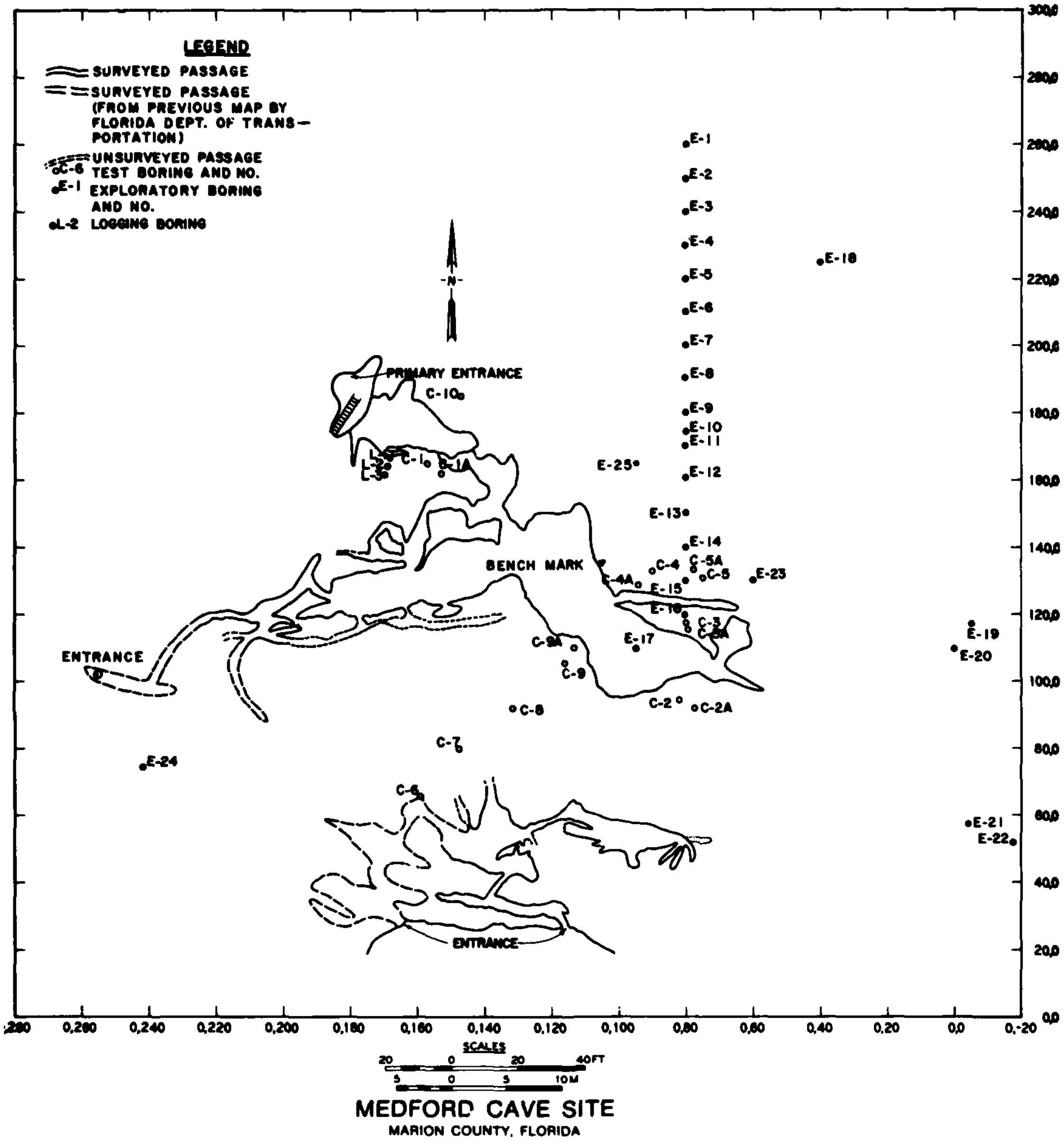


Figure 2. Plan map of the Medford Cave site, Marion County, Fla.

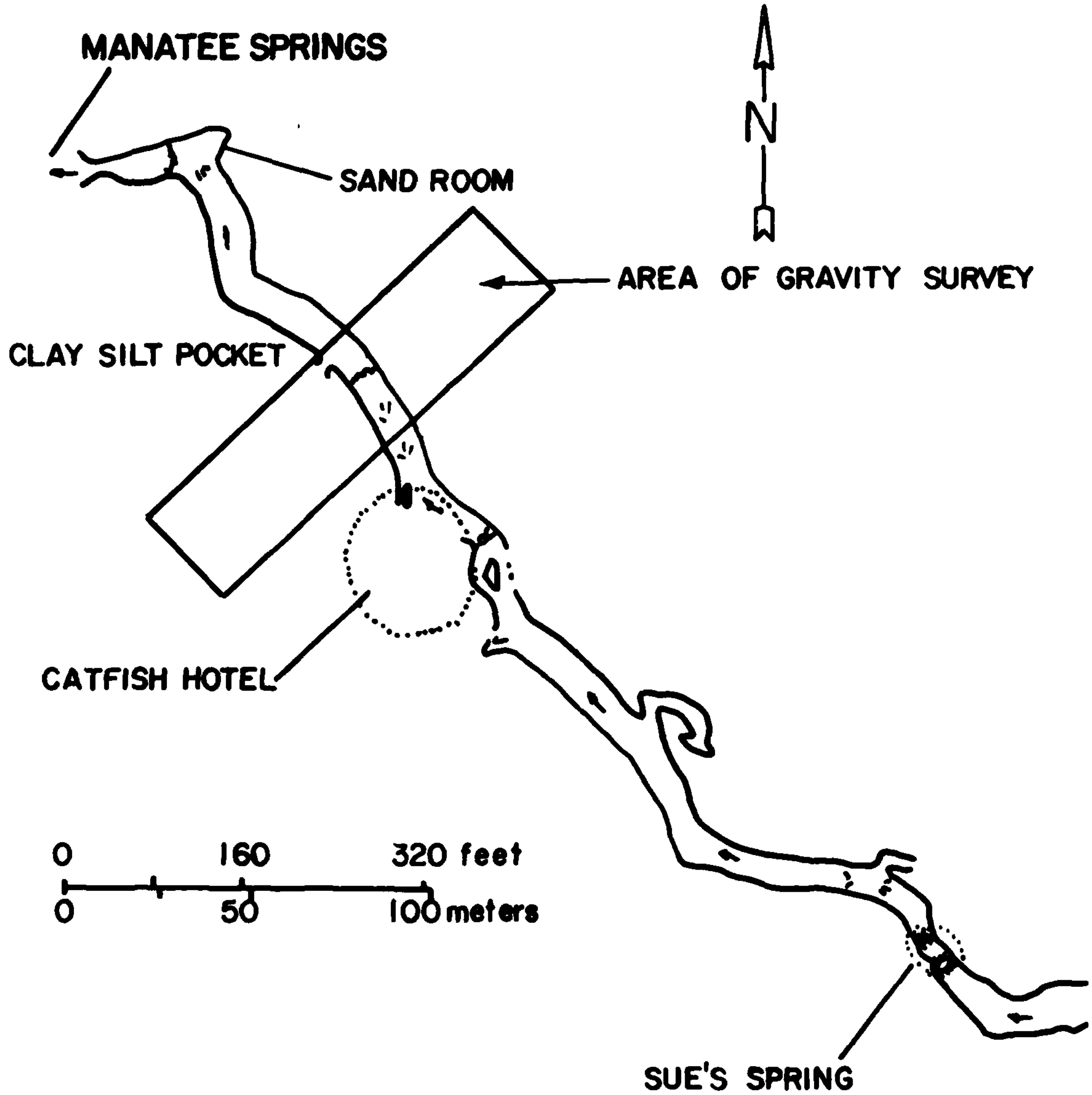


Figure 3. Plan map of the Manatee Springs site, Levy County, Fla.

clandestine tunnels) presents problems for facility foundations as well as for base perimeter security.

Purpose

5. The purpose of this report is to document new and/or improved analytical and data processing techniques for interpretation of the results of geophysical surveys. The work has involved (a) acquiring, improving, and modifying existing computer codes; (b) writing new computer codes in-house; and (c) producing new computer codes by contract sources. All of the work is designed to improve and speed up data acquisition and processing and to improve and extend capabilities for interpreting engineering properties from geophysical surveys.

Scope

6. Part II of this report covers the resistivity methods, Part III covers the microgravimetric techniques, and Part IV covers the seismic methods. A summary and recommendations for future work are presented in Part V. The coverage of the geophysical techniques is limited to a brief review of the concepts and field procedures of the techniques listed in paragraph 2, followed by computer program documentation and examples of the use of the computer programs. Table 2 is a summary list of all the computer programs documented in this report and gives pertinent features of each as well as where the documentations and program listings can be found.

Table 2

Summary List of Geophysical Computer Programs

Program Name	Primary Function	Program Documentation, Part	Program Listing, Appendix	Language	Operating Mode	Equipment/Facility Requirements	Comments
RESDIR	Compute resistivity sounding data for specified model	II	A	FORTRAN IV	T/S*	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
RESINV	Determine subsurface model from resistivity field sounding data	II	C	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
RESDAT	General purpose resistivity field data processing program	II	D	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
TIDES	Computes theoretical earth gravity tide	III	E	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
TALGRAD	Computes gravity and gravity gradients for polygonal cross section models	III	F	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
HILBERT	Computes Hilbert transform of discrete profile data	III	G	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
SEISDIG	Digitize analog seismic records	IV	H	BASIC	M/C††	Tektronix 4051 Minicomputer Tektronix Hard Copy Unit or Printer† Tektronix Digital Plotter Tektronix Graphics Tablet/ Four Button Cursor	1

(Continued)

* Time sharing
** Currently operational on Honeywell DPS-1
† Optional
†† On-line mini/micro computer facility
1 Easily adapted to other mini/micro computer systems

Table 2 (Concluded)

Program Name	Primary Function	Program Documentation, Part	Program Listing, Appendix	Language	Operating Mode	Equipment/Facility Requirements	Comments
SEISPLOT	Plot Seisdig data files	IV	H	BASIC	M/C	Tektronix 4051 Minicomputer Tektronix Digital Plotter	1
REFINT	Interpret seismic refraction time-distance plots	IV	H	BASIC	M/C	Tektronix 4051 Minicomputer Tektronix Hard Copy Unit or Printer† Tektronix Graphics Tablet/ Four Button Cursor	1
DOMER	Processes Rayleigh-wave data from analog refraction records	IV	H	BASIC	M/C	Tektronix 4051 Minicomputer Tektronix Hard Copy Unit or Printer Tektronix Digital Plotter Tektronix Graphics Tablet/ Four Button Cursor	1
REFRDIR	Computes time-distance data for specified model	IV	I	FORTRAN IV	T/S*	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
REFRINV	Determines subsurface model from seismic refraction field data	IV	J	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal	
CROSSHOLE	Interprets crosshole seismic survey data	IV	K	FORTRAN IV	T/S (or Batch)	Mainframe Computer** T/S Terminal	2
PLOT 2	Produces on-line plot at T/S terminal location with linear axes	App B	B	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	3
PLOTLL	Produces on-line plots at T/S terminal location with logarithmic axes	App B	B	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	3

* Time sharing
** Currently operational on Honeywell DPS-1
† Optional
†† On-line mini/micro computer facility
1 Easily adapted to other mini/micro computer systems
2 Only selected options have been reformatted for output on T/S Terminal
3 Uses standard Cal/Comp instruction commands

PART II: SURFACE ELECTRICAL RESISTIVITY METHODS

Background

7. All surface electrical resistivity methods considered in this section involve linear four-electrode geometries (arrays). The four most common electrode arrays are illustrated in Figure 4. In each of the four arrays, an electrical current I is input to the ground at electrodes C_1 and C_2. Electrodes P_1 and P_2 are used to measure a potential difference ΔV. The following equation can be used to calculate an apparent resistivity ρA

$$\rho A = K_G \frac{\Delta V}{I} \tag{1}$$

where K_G is a geometric factor which depends on the array type and electrode spacings within the array. For the Wenner array (Figure 4a), $K_G = 2\pi a$; and for the Schlumberger array $K_G = \pi s \left[(L/s)^2\ 1/4\right]$, where $s = P_1P_2$ and $L = C_1C_2/2$ (generally $L \geq 5s$) . In the pole-dipole array, electrode C_2 is placed at effective infinity (generally $C_2P_2 > 5$ to 10 times the maximum value reached by C_1P_2 during a survey is sufficient); and $K_G = 2\pi R_1R_2/(R_2-R_1)$, where $R_1 = C_1P_1$ and $R_2 = C_1P_2$ $(R_2 - R_1 = P_1P_2)$. Finally, for the dipole-dipole array, $K_G = \pi rn(n^2 - 1)$, where $r = C_1C_2 = P_1P_2$ and $C_1P_1 = C_2P_2$ nr.

8. The resistivity given by Equation 1 is called an apparent resistivity since it may not actually be the true resistivity of any of the subsurface materials. This fact can be illustrated by a conceptual example: consider a layer of soil over a bedrock which is very thick. If, say, a Schlumberger or Wenner electrode array is used to study the example just presented, the following facts can be stated: (a) for electrode spacings a or L much smaller than the soil layer thickness, the measured apparent resistivity (ρ_A) approaches the true resistivity of the soil (ρ_1) ; (b) for electrode spacings a or L much greater than the soil layer thickness, the apparent resistivity approaches the true resistivity of the bedrock (ρ_2) ; and (c) for a or L values

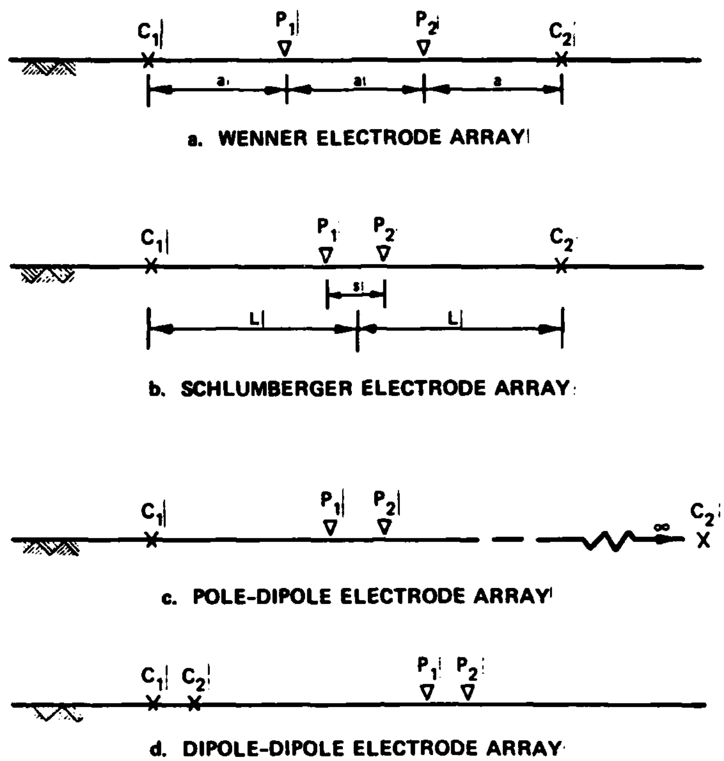


Figure 4. Four commonly used resistivity electrode arrays

between these two extremes, the apparent resistivity will be intermediate in value (i.e., the measured apparent resistivity will be a volume average of ρ_1 and ρ_2, with the volume included in the measurements increasing with a and L).

9. Two types of surface resistivity surveys can be conducted, and these surveys will be termed horizontal profiling and vertical soundings. In horizontal profiling surveys, electrode spacings are selected and the entire array is moved along the surface keeping the spacings constant. If a set of parallel profile lines is surveyed in this manner, the result will be a grid of apparent resistivity values over an area for a constant electrode geometry; this grid of data can then be contoured to produce a resistivity map. Horizontal resistivity profiling is designed to investigate lateral geologic variations above

an essentially constant depth of investigation. Frequently the electrode spacings for horizontal profiling are selected on the basis of the results of a vertical resistivity sounding (described below).

10. In vertical sounding, the electrode array is expanded symmetrically about a center point and it is assumed that variations in apparent resistivity as the electrode spacing increases reflect changes in true resistivity as a function of depth beneath the surface point of symmetry of the array. The objective in vertical sounding interpretation is to determine the true resistivity versus depth variation from the apparent resistivity versus electrode spacing data. The result will generally be a layered model consisting of layer thickness and associated true resistivities. Interpretation is usually accomplished by curve matching (i.e., matching field data curves with standard curves) or by the use of a resistivity inversion computer program. Useful discussions of resistivity theory, field methods, interpretation procedures, and case histories can be found in Telford et al. (1976), Department of the Army (1979), Keller and Frischknecht (1966), Zohdy et al. (1974), and Butler and Murphy (1980).

11. In this section, three computer programs will be described which assist in the processing and interpretation of resistivity field data. The first two programs, RESDIR and RESINV, are used for interpreting vertical resistivity sounding surveys. The third program, RESDAT, is a general purpose resistivity processing program. Also, examples of the use of the processed and interpreted resistivity results will be presented as illustrations and as suggestions for future work. All of the programs are written in FORTRAN IV for use on the U. S. Army Engineer Waterways Experiment Station (WES) Time-Sharing system; use of the plotting options requires a Tektronix Digital Plotter on-line at the terminal.

RESDIR: A Computer Program for Solution of the Direct Problem in Resistivity Sounding

12. The direct or forward problem in electrical resistivity sounding consists of specifying a resistivity model and then calculating

the apparent resistivities which would be observed by a given electrode array on the surface of the model. For present purposes, the class of models consisting of horizontal layers with resistivities ρ_i and thicknesses h_i is considered, where i specifies the i^{th} layer; this class of models is illustrated in Figure 5. Unlike the inverse problem

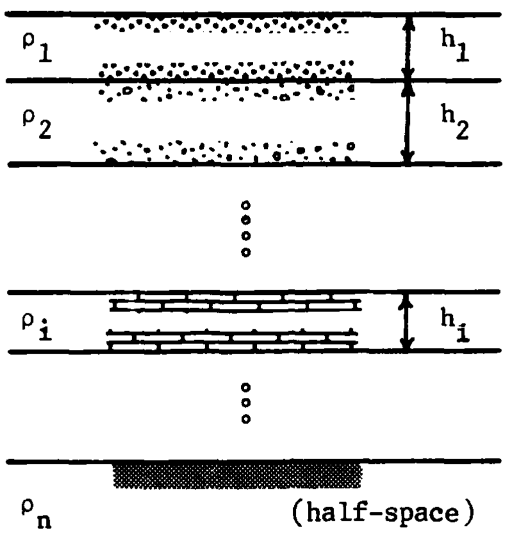


Figure 5. Resistivity model, n-layers with horizontal interfaces

of deducting a possible model directly from field resistivity sounding data, the direct resistivity sounding problem is unique; i.e., for a given electrode geometry and resistivity model, there is only one posible sounding curve.

13. RESDIR is a FORTRAN computer program which solves the direct problem in resistivity sounding using linear filter theory (Ghosh, 1971a, b). The filters were derived by Davis (1979a) and the program described in Davis (1979a, b) and Mooney (1979). The program was adopted for use on the WES computer time-sharing system and an output plotting option was added. For a given electrode array, Wenner, Schlumberger, or axial dipole-dipole, the program computes and plots the apparent resistivity sounding curve. Beginning with a user-specified initial electrode

spacing, the apparent resistivity values are computed at six points per decade of electrode spacing. A listing of RESDIR is presented in Appendix A.

Input data

14. All data are input in a free-field format with prompting messages; i.e., the specified parameters are input consecutively, separated by commas. Individual input lines and parameters are described below and also in comment statements in the program listing (Appendix A). The units must be consistent, e.g., if resistivities in ohm-m, then layer thicknesses and electrode spacings must lie in m .

Input No. 1: INDEX

Index--specifies array type; enter 1 for Schlumberger array, 2 for Wenner array, or 3 for dipole-dipole array.

Input No. 2: SPAC, E, M

SPAC--smallest a-spacing (for Wenner array), or smallest L-spacing (for Schlumberger array).

E--specifies number of layers in the chosen model.

M--specifies total number of apparent resistivity values to be calculated (at rate of six per decade beginning with SPAC)

Input No. 2A: IX

Input only for dipole-dipole array (INDEX = 3).

IX--enter 0 if r is varied (n constant) or enter 1 if n is varied (r constant).

Input No. 2B: N-values

If IX = 0, enter only one N-value
If IX = 1, enter M N-values.

Input No. 3: Model Parameters (P(I), I = 1, 2E - 1)

Enter E-1 layer thicknesses, immediately followed by E layer resistivities.

The above input sequence is repeated for additional models; normal program selection is terminated by inputting 0 (zero) for INDEX.

Program input

15. Printed output from the program consists of a listing of the input model and then a listing of the computed apparent resistivities and

corresponding electrode spacings. Optional plots of apparent resistivity versus electrode spacing for Wenner or Schlumberger arrays can be generated; either arithmetic or logarithmic plots can be selected. The plots are generated by a CALL PLOT2 (X, Yn, N) or CALL PLOTLL (X, Y, N) command, where X and Y are the parameters to be plotted and N is the number of values. PLOT2 and/or PLOTLL are used in nearly all the programs in this report and are documented in Appendix B; the plot specification input sequence is the same for all programs in this report.

Examples

16. RESDIR can be used to generate sounding curves for hypothetical field situations and as an aid in interpreting field sounding data.

17. Example 1. Consider the hypothetical two-layer case shown in Figure 6; the plots demonstrate the appearance of the sounding curves

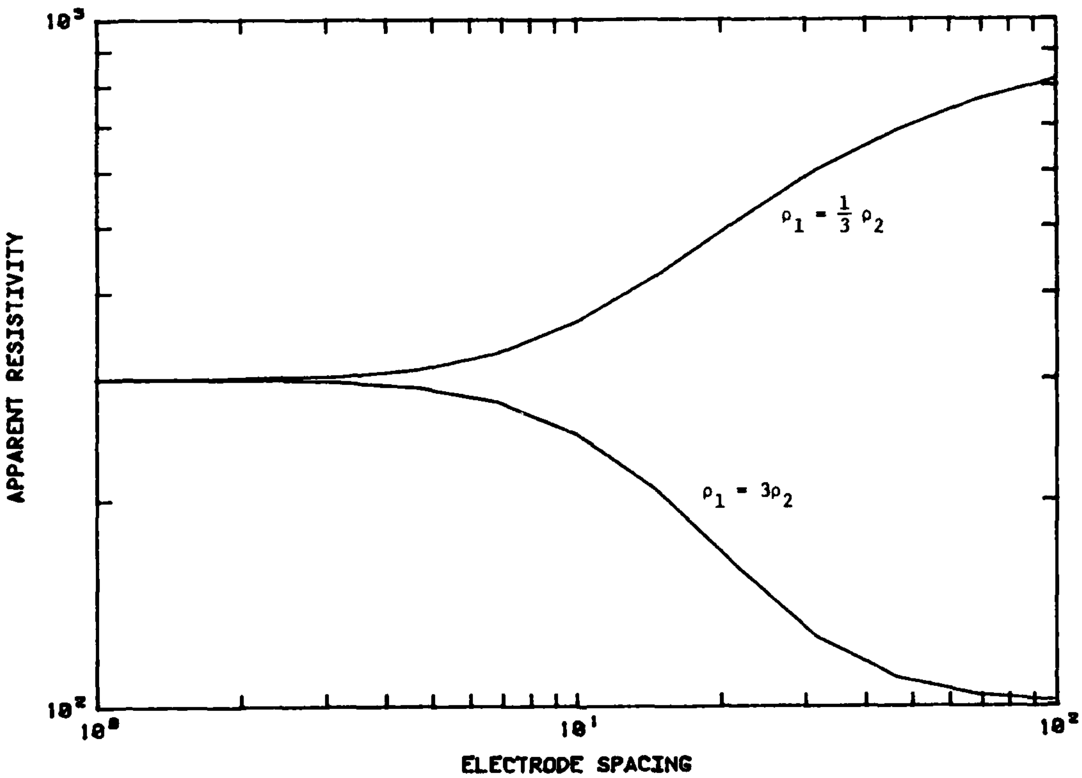


Figure 6. Two-layer resistivity sounding curves, Wenner electrode array, computed using RESDIR (For both cases, $h_1 = 10$ m and $\rho_1 =$ 300 ohm-m.)

using a Wenner array for two cases, where $\rho_1 = 1/3\rho_2$ and where $\rho_1 = 3\rho_2$; the layer thickness is the same for both cases. The input data and program output are shown in Figure 7 for the case where $\rho_1 = 1/3\rho_2$.

18. Example 2. As an example of the use of RESDIR for generation of sounding curves for hypothetical field situations, consider the three-layer model in Figure 8. The objective of this model is to simulate the case of an alluvial aquifer above a resistant basement; i.e., layer 1 represents an unsaturated sandy soil, layer 2 represents the alluvial aquifer (saturated sandy soil), and layer 3 represents the resistive basement rock. The aquifer thickness is constant at 10 m, and three different depths to the top of the aquifer are considered. Sounding curves for the three cases using a Schlumberger array are also shown in Figure 8. Results such as shown in Figure 8 could be used for assessing the feasibility and limitations of resistivity sounding for detecting the presence of an aquifer.

RESINV: A Computer Program for Solution of the Inverse Problem in Resistivity Sounding

19. The inverse problem in resistivity sounding requires that a model be deduced from a set of resistivity sounding field data. Use of the program RESINV to solve the inverse problem requires that an initial model (number of layers, layer thicknesses, and resistivities) be specified; this initial model can be determined by examination of the field data. The number of layers in the initial model will not be altered by the program; however, the layer thicknesses and resistivities will be iteratively adjusted until a good fit to the field data is achieved. The inversion scheme is described in Davis (1979a) and the program is described in Davis (1979a, b) and Mooney (1979). Davis used an inversion procedure developed originally by Merrick (1977) for Schlumberger sounding data. The iterative adjustment is accomplished using Marquardt's algorithm (Marquardt, 1963), which is an optimized combination of Newton-Gauss and gradient inversion methods.

```
INPUT NO. 1---INDEX (ARRAY TYPE)
=2
INPUT NO. 2--SPAC,E,M
=1,2,13

INPUT NO. 3, MODEL PARAMETERS, THICKNESSES(H) AND RESISTIVITIES(R)---H
(1),H(2),....,H(E-1),R(1),....,R(E)
=10,300,900

APPARENT RESISTIVITY VALUES

WENNER ARRAY

2 LAYER MODEL.

     LAYER NO.          THICKNESS          RESISTIVITY
         1               10.000              300.000
         2                                   900.00

      SPACING          RHO
        1.00         300.114
        1.47         300.369
        2.15         301.155
        3.16         303.505
        4.64         310.133
        6.81         326.964
       10.00         363.097
       14.68         425.195
       21.54         509.295
       31.62         602.067
       46.42         689.895
       68.13         763.446
      100.00         818.245
```

Figure 7. Input data to RESDIR and program output for the case $\rho_1 = 1/3\rho_2$ shown in Figure 6 (User input is indicated by an '=' sign.)

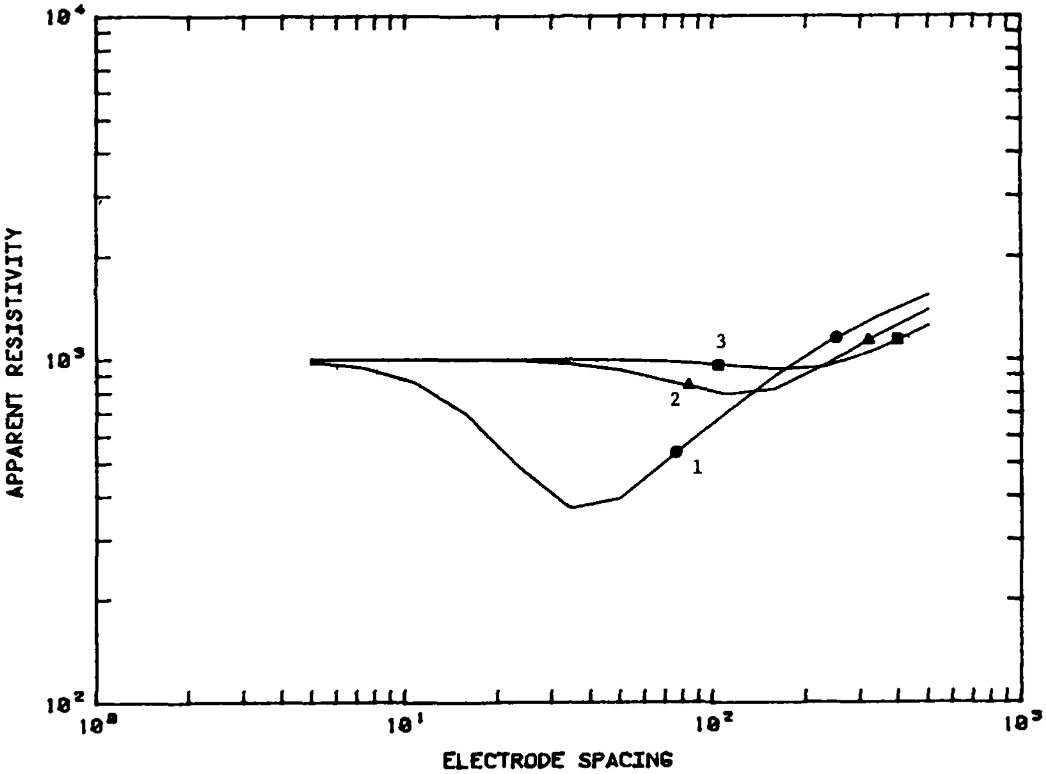


Figure 8. Schlumberger array sounding curves for three-layer model with ρ_1 = 1000 ohm-m , ρ_2 = 100 ohm-m, ρ_3 = 2000 ohm-m, and h_2 = 10 m (Case 1--h_1 = 10 m ; Case 2--h_1 = 50 m; Case 3--h_1 = 100 m.)

20. Using the techniques of RESDIR, apparent resistivities for the initial model are computed and compared with the field data. A derivative matrix consisting of partial derivatives of apparent resistivity with respect to each model parameter is computed. Corrections to each model parameter are determined from a generalized inversion of the derivative matrix. The corrections are added to initial model and a new set of apparent resistivities and layer thicknesses are computed. This procedure is continued until the root-mean-square (rms) error falls below a specified convergence criterion.

21. Even though a given initial model may be adjusted to a final model which results in computed apparent resistivities that closely fit field data, the model is not unique and may not be geologically correct or even reasonable. Any independent geologic control which is known for

the site should be utilized to constrain the inversion process; any of the model parameters can be specified as fixed, as dictated by geologic control, and will not change during the inversion process. In general, the minimum number of layers required to produce the essential features of the field sounding curve should be used initially, adding layers for subsequent models only if a good fit is not achieved with the minimum number of layers. The initial model can be chosen by the use of graphical and empirical techniques, such as curve-fitting, asymptotes, and inflection points of field curves, Barnes layer method, Moore cumulative method, inverse slope method, or, in many cases, just by examination of the field-sounding curve (Hugdahl and Dahl, 1979; Barnes, 1954; Sanker Narayan and Ramanujachary, 1967; Moore, 1945; Telford et al., 1976). The examples which follow will illustrate some of these techniques. Successful use of RESINV depends to a greater extent on the particular set of data involved, the quality of the data (including lack of lateral effects* in the data), and the experience of the interpreter. The best results with RESINV will be achieved when there is good geologic control and/or when the interpreter is familiar with the geologic sequence likely to be encountered in a particular area.

Input data

22. All data are input in free-field format. A program listing for RESINV is in Appendix C. Input data requirements are as follows:

Input No. 1: INDEX

INDEX--array type; enter 1 for Schlumberger array, 2 for Wenner array, or 3 for dipole-dipole array

Input No. 2: SPAC, E, M, NN, RMSC

SPAC--smallest a-spacing (for Wenner array) or smallest L-spacing (for Schlumberger array)

E--specifies number of layers for model

* Lateral effects, i.e., lateral or horizontal changes in resistivities of near-surface materials, can introduce errors in the inversion model and in some cases may result in fictitious layers in the model. Many times, lateral effects can be easily recognized on resistivity shifting of curve segments (for Schlumberger soundings) or graphical smoothing.

M--number of field readings

NN--number of fixed layer (model) parameters

RMSC--root-mean-square error cutoff value in percent (typically use 1 to 5 percent).

Input No. 2A: IX (Input only for dipole-dipole array, INDEX = 3)

IX--enter 0 if r is varied (n constant) or enter 1 if n is varied (r constant)

Input No. 2B: N

If IX = 0, enter one n-value
If IX = 1, enter M n-values

Input No. 3: INDX1

INDX1--enter 1 if field data are at perfectly logarithmic electrode intervals, or enter 0 if otherwise

Input No. 3A: (SN(1), SN(2), ...SN(M)

SN(1)--electrode spacings, M-values. Skip if INDX1 = 1.

Input No. 4: R2(1), R2(2), ...R2(M)

R2(1)--field apparent resistivities, M-values, each corresponding to SN(1)

Input No. 5: Model parameters (P(I), I = 1, 2E - 1)

Enter E-1 layer thicknesses, immediately followed by E layer resistivities

Input No. 6: (NF(I), I = 1) NN)

NF(I)--fixed parameters. There should be a total of NN numbers specifying which of the model parameters in Input No. 5 are to be fixed. The NF number assignment is consecutively from NF = 1 for P(1) to NF = 2E - 1 for P(2E - 1).

23. Program execution will terminate when (a) the rms error drops below RMSC, (b) the program completes 15 iterations, (c) a minimum is reached before either (a) or (b) occurs and all further iterations increase the sum of squares (in this case, the note "J1 = JMAX--TRIAL MODEL will not converge," or (d) INDEX is set equal 0. The program will cycle to accept another set of data until INDEX = 0 is input.

Program output

24. Program output consists of printed listings of the results of the input initial model calculations (iteration No. 0) and computed

final model calculations and plots of field data, initial model, and final model. The output sequence and content is as follows:

a. The results of iteration No. 0 are printed; these consist of a tabular listing of the input initial model parameters, tabular listing of electrode spacing, computed model apparent resistivity, and field apparent resistivity, and finally the rms error.

b. A plot of the sounding curve for the input initial model is now generated (see Appendix B for plot specification input sequence).

c. An optional plot of the field sounding curve can now be generated superimposed on the plot in b.

d. The results of the final iteration are printed (including final rms error).

e. A plot of the sounding curve for the final (best-fit) model is generated, which can be superimposed on the plots in b and c.

Examples

25. Example 1. In order to illustrate the input parameter sequence and the capability of RESINV to converge to a known model, the sounding curve corresponding to case 1 in Figure 8 was digitized and the resulting apparent resistivity versus L-spacing data were input to RESINV. The apparent resistivity values for 12 selected electrode spacings (from 6 to 400 m) were estimated directly from the log-log plot, so the input data would have "noise" due to errors in estimating values from the plot. An initial three-layer model was deduced from the general features of the sounding curve in Figure 8 and input to RESINV. Results of the use of RESINV to find a best-fit, three-layer model to the input data are shown in Figure 9 as Case I; the known model and the initial model are also shown. The best-fit, three-layer model labeled Case II in Figure 9 is the result of inputting the exact equally spaced (logarithmically) output data from RESDIR corresponding to Figure 8, using the same initial model as in Case I. For Case II, the program converges exactly to the known model; and for Case I, the final model is acceptable, with the greatest discrepancies for the second layer parameters. Figure 10 shows the input data and tabular output for Case I, and Figure 11 shows the plotted output (field data sounding curve and sounding curve and sounding curves for the initial and best-fit models).

Known Model	Initial Model Used for Input to RESINV	Case I RESINV Best Fit Model (8 Iterations*)	Case II RESINV Best Fit Model (7 Iterations**)
h_1 = 10.00 ρ_1 = 1000.00	h_1 = 20.00 ρ_1 = 1000.00	h_1 = 9.88 ρ_1 = 980.94	h_1 = 10.00 ρ_1 = 1000.00
h_2 = 10.00 ρ_2 = 100.00	h_2 = 30.00 ρ_2 = 300.00	h_2 = 13.49 ρ_2 = 135.56	h_2 = 10.02 ρ_2 = 100.15
ρ_3 = 2000.00	ρ_3 = 1500.00	ρ_3 = 1899.98	ρ_3 = 2000.00

* RMS error = 1.026; model began to diverge with 9th iteration
** RMS error = 0.002

Figure 9. Demonstration of ability of RESINV to converge to a known three-layer model from an initial model guessed from qualitative features of the sounding curve (calculated with RESDIR); Case I - arbitrarily spaced data with errors and Case II - equal logarithmically spaced exact data

```
=1
=6,3,12,0,1
=0
=6,8,10,20,30,40,60,80,100,200,300,400
=950,900,870,560,400,370,440,550,650,1020,1200,1300
=20,30,1000,300,1500


RESISTIVITY INVERSION PROGRAM

SCHLUMBERGER ARRAY


ITERATION NO.   0

LAYER NO.        THICKNESS    RESISTIVITY     THICK*RES    THICK/RES
    1               20.00      1000.000       *********       0.020
    2               30.00       300.000       9000.000        0.100
    3                          1500.000

               SPACING    MODEL RHO   FIELD RHO

                 6.000     996.996     950.000
                 8.807     990.498     869.033
                12.927     972.391     783.348
                18.974     926.422     587.184
                27.850     831.707     420.305
                40.878     694.559     370.628
                60.000     586.079     440.000
                88.068     588.922     591.563
               129.266     698.790     783.237
               189.737     855.054     992.875
               278.495    1017.511    1170.905


          RMS ERROR =  45.605

ITERATION NO.   8

LAYER NO.        THICKNESS    RESISTIVITY     THICK*RES    THICK/RES
    1                9.88       980.942       9690.678        0.010
    2               13.49       135.556       1828.021        0.099
    3                          1899.991

               SPACING    MODEL RHO   FIELD RHO

                 6.000     948.398     950.000
                 8.807     893.947     869.033
                12.927     775.896     783.348
                18.974     591.555     587.184
                27.850     419.617     420.305
                40.878     358.763     370.628
                60.000     447.079     440.000
                88.069     592.626     591.563
               129.266     773.012     783.237
               189.737     976.919     992.875
               278.495    1139.910    1170.905


          RMS ERROR =   1.026
```

Figure 10. RESINV input data and tabular output for Case I, Figure 9 (User input indicated by '=' sign.)

26. Example 2. Figure 12 is a plot of data from a Schlumberger sounding at a site about 8 km northwest of Vicksburg, Miss.* Qualitative evidence for as many as four layers can be seen in the sounding curve. An initial model, deduced from the sounding curve, for input to RESINV is also shown in Figure 12. Results of the inversion by RESINV are shown in Figure 13, where the sounding curve for the best-fit model (also illustrated in the figure) is indistinguishable from the field data.

27. The sequence of resistivities in the model shown in Figure 13 is geologically reasonable for the site: Layer 1 - sand fill; Layer 2 - saturated silts, sands, and clays with organic material; Layer 3 - freshwater sands and gravels; Layer 4 - Yazoo clay. Depth to the top of Layer 4 ($\sim$90 m), however, seems too large, since depths of 60 to 70 m are typical, although the depths are highly variable.

RESDAT: A General Purpose Resistivity Data Processing Program

28. RESDAT is a general purpose computer program for processing resistivity field data. The basic function of the program is to take raw resistivity field data and process the data using Equation 1 to produce tabular and plotted output of resistivity as a function of profile position or electrode spacing for horizontal profiling or vertical sounding, respectively. Data from the following survey types can be accommodated: Wenner profiling, Wenner sounding, Schlumberger profiling, Schlumberger sounding, and pole-dipole surveying. In the case of Wenner and Schlumberger sounding data, an option is available to directly access a subroutine version of RESINV to interpret the data in terms of a resistivity model. For Wenner sounding data, options are available for producing cumulative sum (Moore, 1945) and/or inverse resistivity (Sanker Narayan and Ramanujachary, 1967) plots.

Input data

29. All data are input in free-field format. A program listing for RESDAT is given in Appendix D. If field resistance data ($\Delta V/I$) are

* Figure 12 was produced by the use of RESDAT to process the field data. RESDAT is discussed in the next section of this Part.

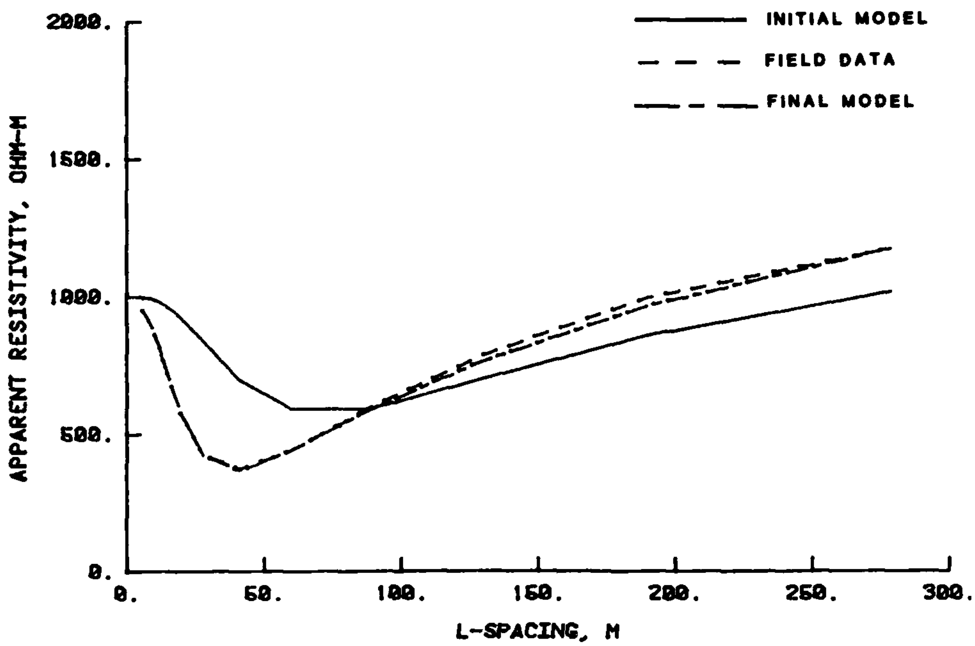


Figure 11. RESINV sounding curves (initial model, field data, and final model) for Case I in Figure 9

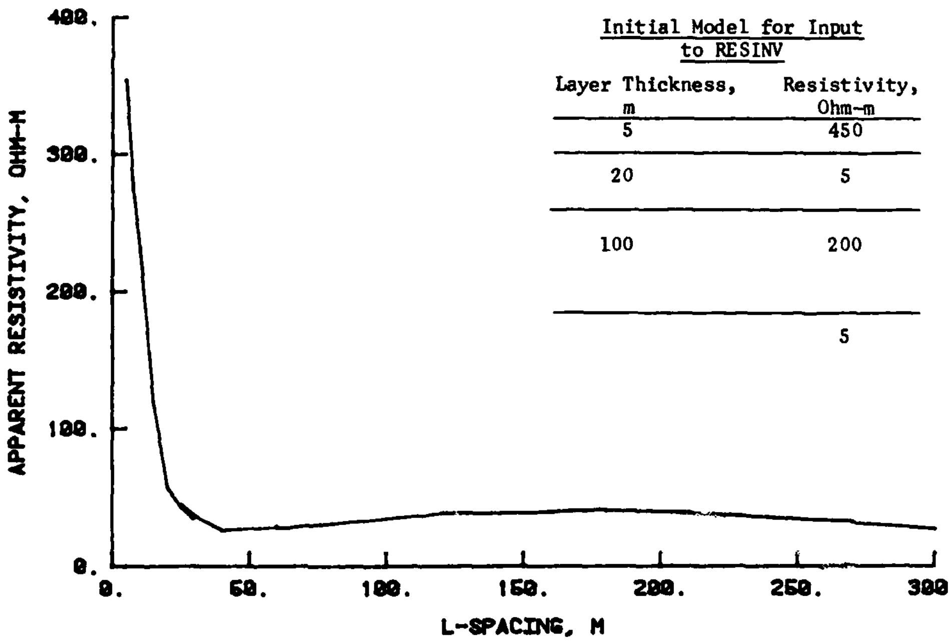
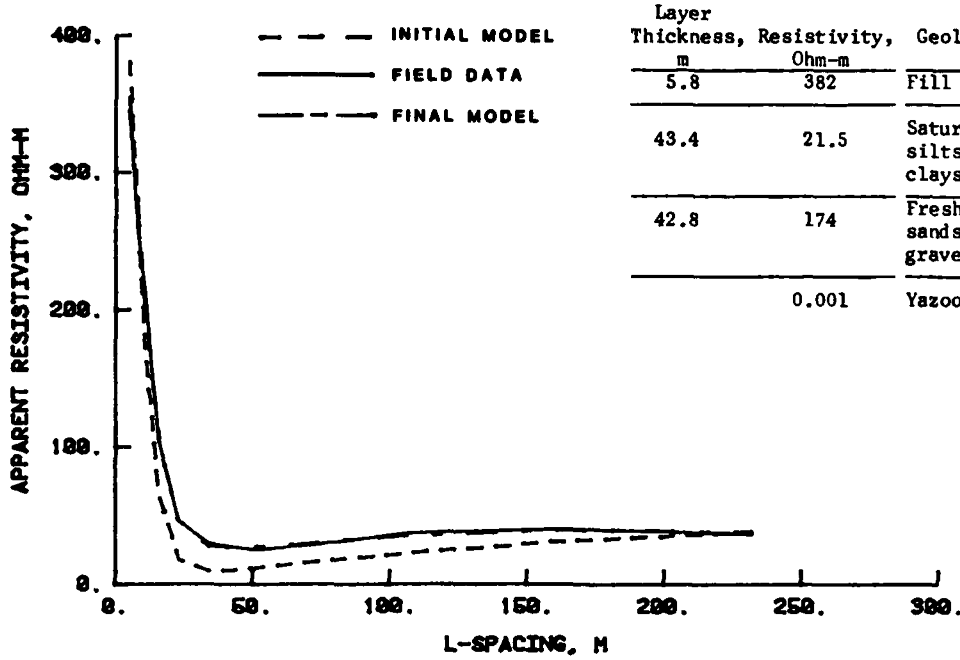


Figure 12. Schlumberger sounding curve obtained at site near Vicksburg, Miss.



Final Model

Layer Thickness, m	Resistivity, Ohm-m	Geology
5.8	382	Fill (Sand)
43.4	21.5	Saturated silts and clays
42.8	174	Freshwater sands and gravels
	0.001	Yazoo Clay

Figure 13. Results of RESINV inversion of field sounding curve and initial model shown in Figure 12

in ohms and electrode spacings are in m (ft), then resistivities will be in ohm-m (ohm-ft). Input data are explained as follows:

Input No. 1: Survey Type

1--Wenner profiling
2--Schlumberger profiling
3--Wenner sounding
4--Schlumberger sounding
5--Pole-dipole survey

For Survey Type 1:

Input No. 2: A, N

A--a-spacing (see Figure 4a)
N--number of data points

Input No. 3: X1, R1, X2, R2, ...SN, RN

X_i--profile coordinate of i^{th} data point
R_i--field resistance ($\Delta V/I$) value for i^{th} data point

Input No. 4:

Is factor (2π) included in field resistance data?
Type _1_ for yes and _2_ for no.

For Survey Type 2:

Input No. 2: S, L, N

S, L--S- and L-spacings (see Figure 4b)
N--number of data points

Input No. 3: X1, R1, X2, R2, ..., XN, RN

Same as for Survey Type 1.

Input No. 4:

Same as for Survey Type 1.

For Survey Type 3:

Input No. 2: POS

POS--up to 72 characters describing the location of the resistivity sounding or other pertinent information

Input No. 3: N

N--number of data points

Input No. 4: A1, R1, A2, R2, ...AN, RN

A_i--a-spacing for the i^{th} data point
R_i--field resistance value for the i^{th} data point

Input No. 5:

Is factor (2π) included in resistance values?
Yes (1), No (2)

Input No. 6:

Do you want a cumulative sum plot? Yes (1), No (2)

Input No. 7:

Do you want an inverse resistivity plot? Yes (1), No (2)

Input No. 8:

Do you want to interpret data? Yes (1), No (2)
If Yes, inputs 8A and 8B are required.

Input No. 8A: E, NN, RMSC

E--number of model layers
NN--number of fixed model parameters
RMSC--rms cutoff in percent

Input No. 8B: (P(I), I = 1, 2E - 1)

Model parameters; same as RESDIR Input No. 3.

For Survey Type 4:

Input No. 2: POS

Same as for Survey Type 3

Input No. 3:

Is factor (2π) included in field resistance values?
Yes (1), No (2)

Input No. 4: N

N--number of data points

Input No. 5: S1, L1, R1, S2, L2, R2, ...SN, LN, RN

S_i, L_i--S- and L-spacing for i^{th} data point

R_i--field resistance value for the i^{th} data point

Input No. 6:

Do you want to interpret data? Yes (1), No (2)
If yes, inputs 6A and 6B are required.

Input No. 6A: E, NN, RMSC

Same as for input No. 8A, Survey Type 3.

Input No. 6B: (P(I), I = 1, 2E - 1)

Model parameters; same as RESDIR Input No. 3.

For Survey Type 5:

Input No. 2: POS

POS--up to 72 characters describing the pole-dipole current electrode station location and profile direction information

Input No. 3:

Is factor (2π) included in field resistance values?
Yes (1), No (2)

Input No. 4: PP, N

PP--potential electrode spacing P_1P_2 (see Figure 4c)
N--number of data points

Input No. 5: CP1, R1, CP2, R2, ...CPN, RN

CP_i--distance from current electrode to first potential electrode C_1P_1 (see Figure 4c) for i^{th} data point

R_i--field resistance value for i^{th} data point

For all five survey types, an option is available, at the end of the output sequence described below, to repeat the input sequence for another data set of the same survey type.

Program output

30. The output of RESDAT will vary depending on survey type as listed below:

a. Survey Type 1: Wenner Profiling Survey

(1) Tabular listing of profile position and apparent resistivity

(2) Plot of apparent resistivity versus profile position

b. Survey Type 2: Schlumberger Profiling Survey

(1) Tabular listing of profile position and apparent resistivity

(2) Plot of apparent resistivity versus profile position

c. Survey Type 3: Wenner Sounding

(1) Tabular listing of a-spacing and apparent resistivity

(2) Plot of apparent resistivity versus a-spacing sounding curve, either linear or log-log

(3) Optional plots of cumulative resistivity sum and/or inverse resistivity versus a-spacing plots

(4) If data interpretation is elected, all the output described for RESINV will follow

d. Survey Type 4: Schlumberger Sounding

(1) Tabular listing of a-spacing, L-spacing, and apparent resistivity

(2) Plot of apparent resistivity versus L-spacing, either linear or log-log

(3) If data interpretation is elected, all the output described for RESINV will follow

e. Survey Type 5: Pole-Dipole Survey

(1) Tabular listing of C_1P_1, C_1P_2, and apparent resistivity

(2) Plot of apparent resistivity versus X, where $X = (C_1P_1 + C_1P_2)/2$, i.e., each value of apparent resistivity is plotted at the profile location which is the midpoint of the potential electrode locations

Examples

31. Example 1. Figure 12 is an example of the use of RESDAT to process and plot field data from a Schlumberger sounding.

32. Example 2. A large portion of the Medford Cave site (see Figure 1) was surveyed by resistivity profiling, using the Wenner array

with a = 40 ft* and 10-ft station spacing along the profile lines. A plot of apparent resistivity for a = 40 ft for one profile line at the Medford Cave site is shown in Figure 14 (apparent resistivity for a = 10 ft is also shown along the same profile line). Apparent resistivity for all the profile lines was input to the general purpose

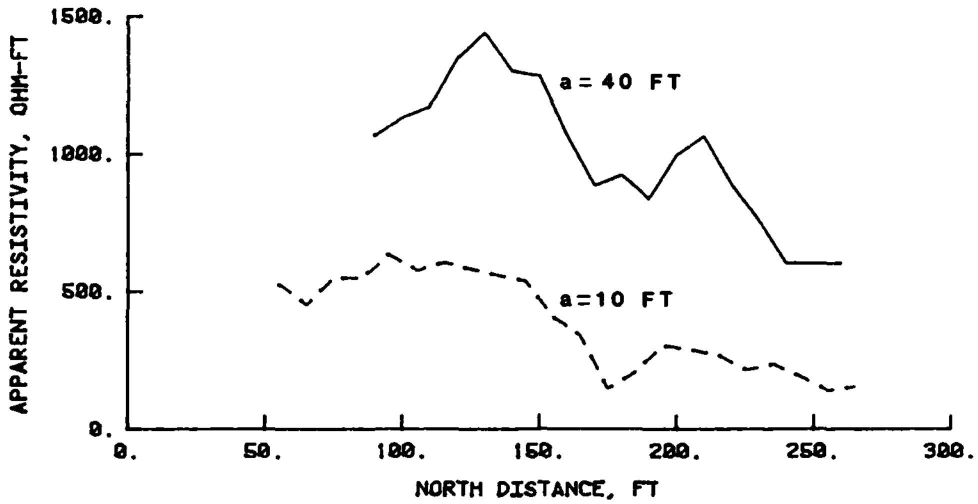


Figure 14. Two horizontal resistivity profiles along the (0,80) to (260,80) line at the Medford Cave Test site (see Figure 2)

contouring program CONTOUR (Tracy, 1974) to produce the apparent resistivity contour map shown superimposed in Figure 15. A plan map of the known cavity system at the site is shown superimposed in Figure 15. An a-spacing of 40 ft was chosen so that the depth of investigation of the resistivity survey would be sufficient to include the effects of the known cavity system. The apparent resistivity contour map is significantly affected by and reflects the presence of the cavity system. Since the "normal background" resistivity is apparently 400 to 600 ohm-ft, the cavity system is responsible for a resistivity anomaly of about 1000 ohm-ft, although the shape of the resistivity contours does not closely match the cavity shape.

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

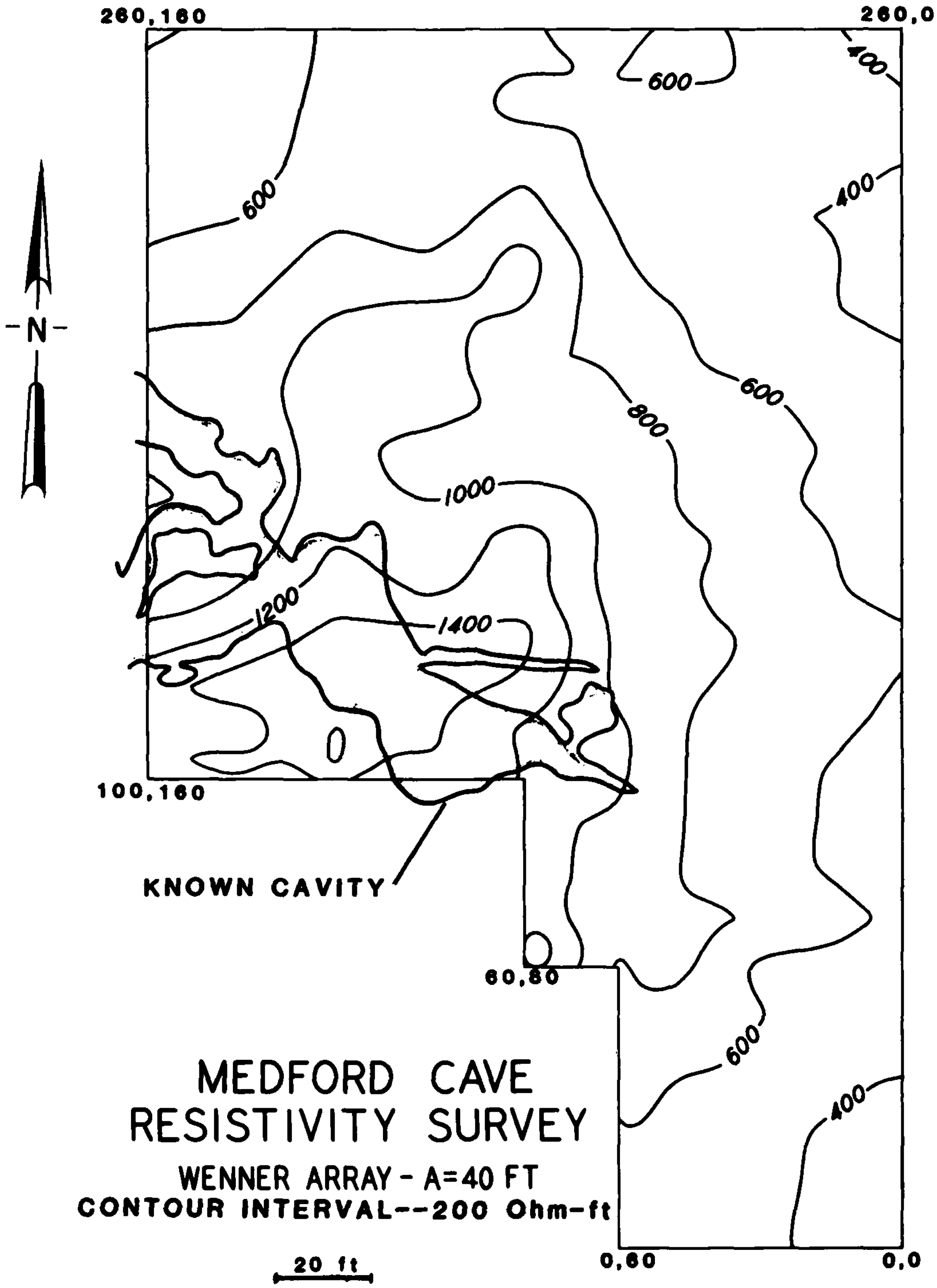

Figure 15. Resistivity contour map for a portion of the Medford Cave site, Wenner electrode array with 40-ft electrode spacing

33. Example 3. The pole-dipole array (Figure 4c) can be used in a survey procedure which combines horizontal profiling and vertical sounding concepts (sometimes called the Bristow-Bates technique; Bristow, 1966; Bates, 1973; Butler and Murphy, 1980; Fountain et al., 1975; and Franklin et al., 1981). The method is well suited for the detection of localized anomalies such as cavities and tunnels. The current electrode C_2 is placed as far away from the survey area as practicable. The potential electrode pair is moved outward on both sides of the current electrode C_1, keeping the spacing P_1P_2 constant (typically 2 to 3 m), to a distance from C_1 somewhat greater than the desired depth of investigation (typically 50 m or less). C_1 is then moved along the profile line to a new location (typically 10 to 20 m from previous location) and the procedure is repeated; overlapping lines are used for multiple coverage. The graphical interpretation procedure, described by Bates (1973) and Fountain et al. (1975), tends to account for the normal variation of resistivity with depth and selects high or low resistivity anomalies with respect to the normal variation. Figure 16 illustrates the graphical procedure for location of anomalies. Circular arcs

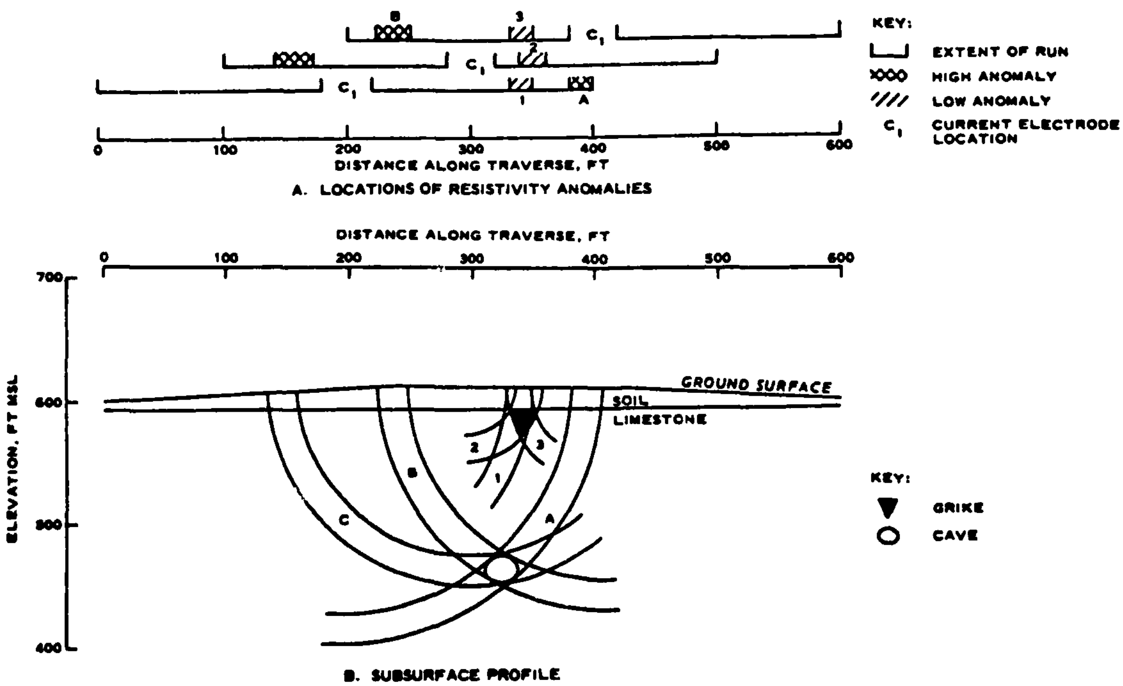

Figure 16. Simplified example of graphical interpretation of pole-dipole resistivity data for anomaly location (Bates, 1973)

are drawn through locations of potential electrodes showing anomalous potential differences, with the C_1 position as center. Intersections of the arcs are assumed to define the locations of anomalies. Figure 16 shows two anomalies located by three traverses with different C_1 locations. The interpretation procedure and the multiplicity and overlapping of data tend to eliminate spurious anomalies and allow discrimination between near-surface anomalies and anomalies at depth. This technique has been used successfully for a number of investigations in karst regions (Bates, 1973; Butler, 1980c; Cooper and Bieganousky, 1978; Fountain et al., 1975) and also for tunnel location in hard rock (Fountain, 1975). These investigations offer strong empirical support for the Bristow-Bates graphical method, in spite of the objection that it does not have a rigorous theoretical basis; i.e., the model on which it is based is qualitative.

34. Several profile lines at the Medford Cave site were surveyed using the pole-dipole survey procedure, and results of the survey along the 80W north-south line will be presented here. Figure 17 shows the pole-dipole sounding results for six locations of C_1 along the profile line, where the field data have been processed and plotted by RESDAT. The potential electrodes were moved out to a distance $X = 80$ ft on each side of each C_1 station, where X is the distance to the center of the potential electrodes. The distance $P_1P_2 = 10$ ft , and X is incremented by 5 ft between measurements. Finally, the distance between C_1 stations is selected as 30 ft; this procedure allows an anomaly near the surface to be defined by as many as seven intersecting hemispherical shells, and the number of possible intersections decreases with depth. The general trend indicated by the sounding data in Figure 17 is increasing apparent resistivity with depth. Numerous anomalies are indicated in the sounding curves, but there is no clear indication of subsurface layering. For purposes of picking anomalies, linear trend lines are used as indicated in Figure 17. Clearly there is a considerable amount of subjectivity in this procedure of picking high and low anomalies; success relies on (a) experience of the interpreter and (b) the considerable redundancy of the data. The results of an analysis of the complete

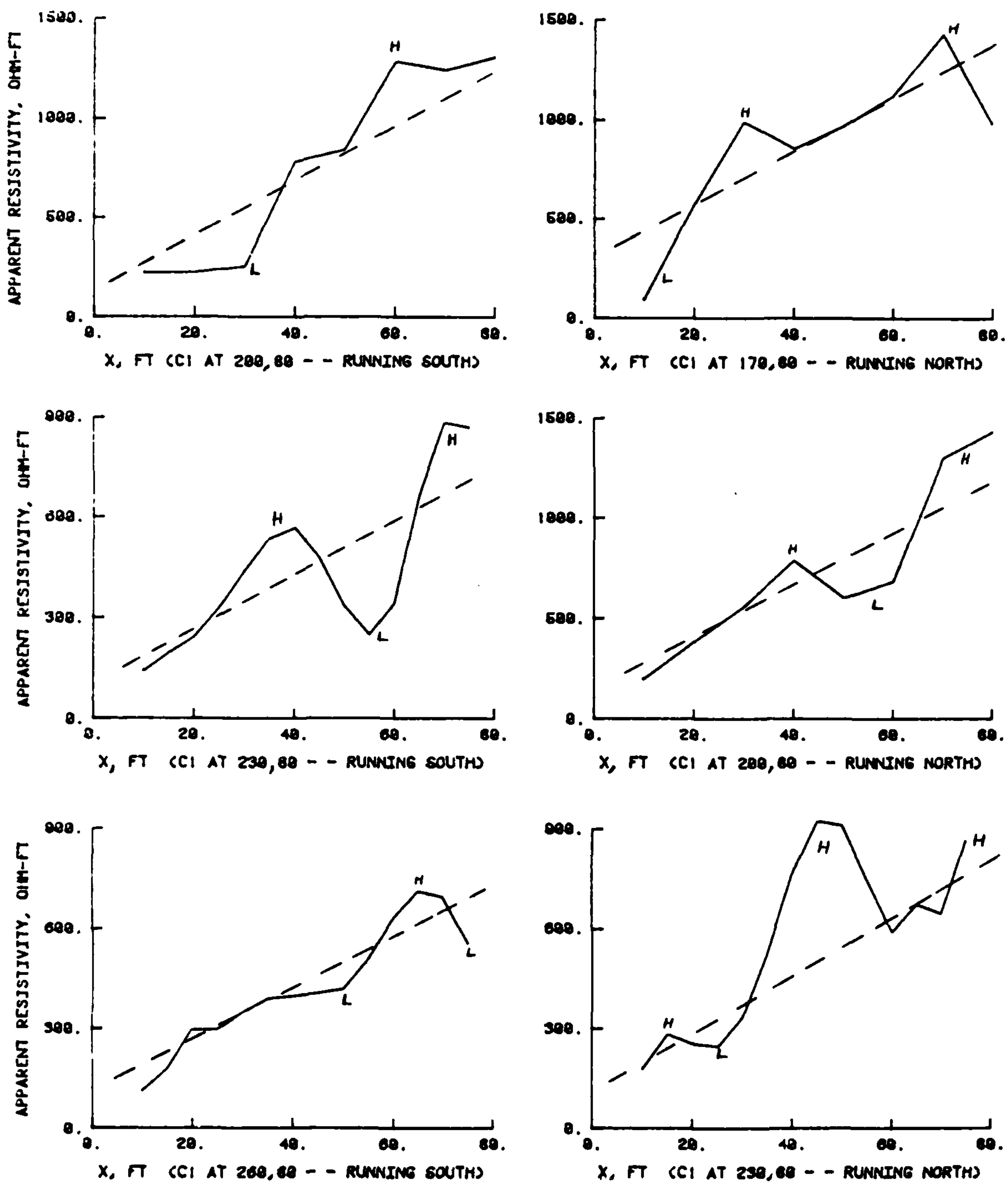

Figure 17. Six pole-dipole sounding curves at 30-ft spacing along the (0,80) to (260,80) line at the Medford cave site

profile line, using the techniques illustrated in Figure 16, are shown in Figure 18. The correlation of the resistivity anomalies with known geologic features (Butler, in press) is quite good.

35. A major drawback to the pole-dipole survey technique just presented is the time required to conduct the field tests and process and interpret the data. Use of RESDAT to process and plot the data is a considerable help, but there is still much which could be done to automate the procedures. An automated resistivity data acquisition system demonstrated by the Southwest Research Institute (SwRI) at the Medford Cave site appears to be a solution to the field time constraint (Fountain and Herzig, 1980). Data are recorded in a digital format with the SwRI system, which can then be processed by the graphical procedure presented here or by an automated interpretation procedure developed by SwRI (Fountain and Herzig, 1980; Spiegel et al., 1980). Although work on the automated technique is continuing at SwRI, currently the technique is limited by the assumption of a single anomaly in a uniform half-space; while the graphical procedure used in this report is subjective, it is not subject to these limitations. A technique which has been successfully utilized at WES for a specific data set is to digitize the locations of high and low anomalies along the profile line and then determine subsurface anomaly locations with an arc-intersection algorithm programmed on a minicomputer; this procedure has not yet been generalized.

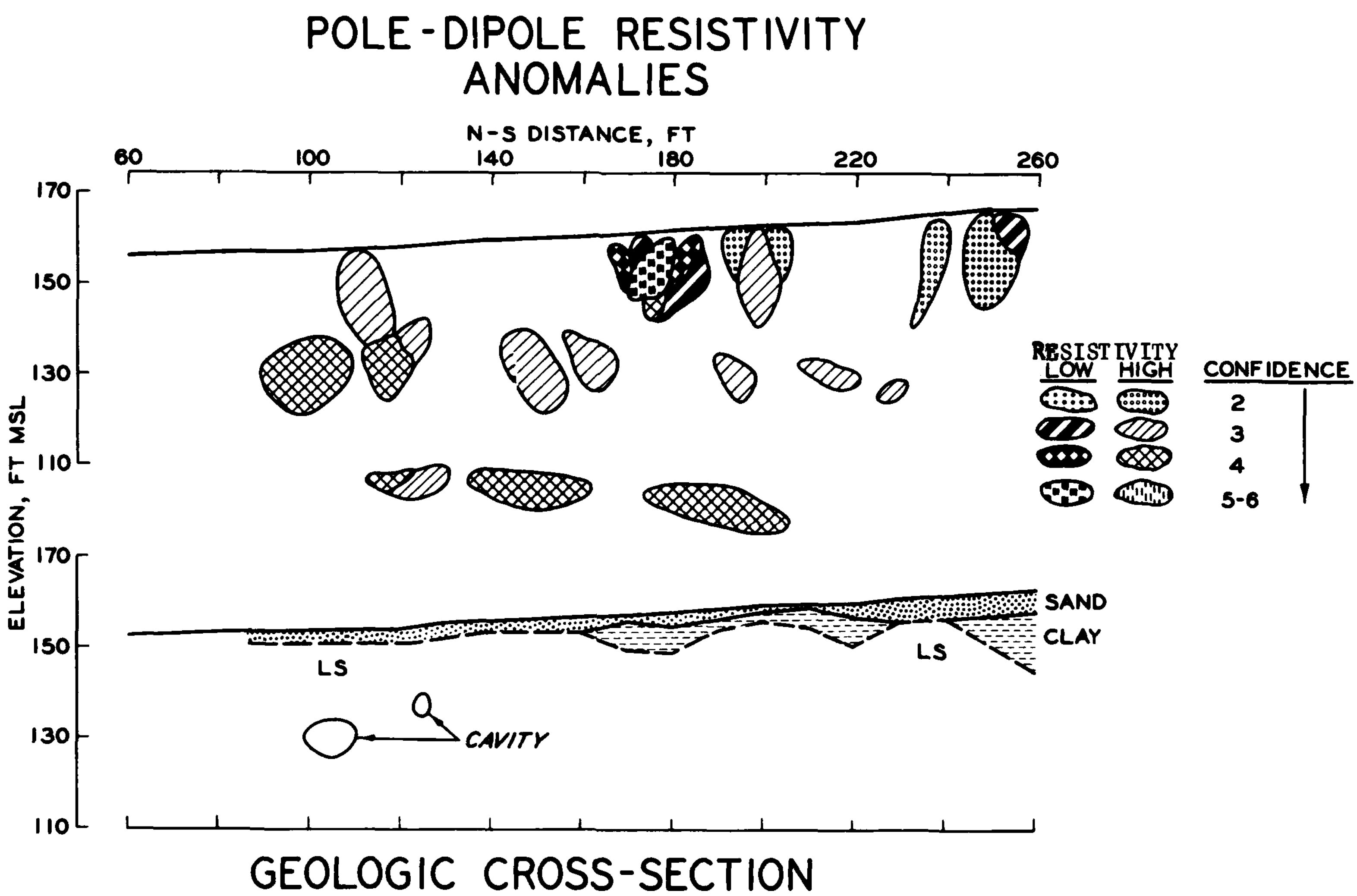

Figure 18. Interpreted pole-dipole resistivity cross section compared with known geology along the (0,80) to (260,80) line at the Medford Cave site (Numbers indicating increasing confidence levels correspond to the number of arc intersections which define the anomaly.)

PART III: MICROGRAVIMETRIC TECHNIQUES

Background

36. Microgravimetry is a geophysical method that offers special advantages over other subsurface exploration methods in a variety of applications. The term "microgravimetry" refers to geophysical investigations involving relative measurements of the acceleration of gravity that require measurement accuracy and precision and instrument sensitivity in the μGal range (1 μGal = 10^{-6} Gal = 10^{-6} cm/sec^2 ≈ 10^{-9} times the earth's normal gravitational acceleration). For geophysical applications, delineation of features with characteristic dimensions of 1 m or less is often desirable, while the maximum depth of interest may typically be 100 m or less. Many attempts to apply gravimetry to geotechnical and shallow structural problems have been disappointing in that the anomalies due to small structures of interest could not be extracted from the data; i.e., only anomalies due to very large or very shallow structures (or some fortuitous combination of the two factors) could be resolved. However, with modern "microgal" gravity meters and refined field and interpretation procedures, microgravimetry is a viable geophysical tool for application to military facility foundation and perimeter security investigations (Butler, 1980a).

37. The gravity method involves the measurement of the vertical component of the gravitational attraction at the surface. The measurement or determination of the first vertical and horizontal derivatives (gradients) of the vertical component of the gravitational attraction can be of considerable fundamental and practical importance. Measurement of the gradients or determination of the gradients from gravity profiles offers two particular advantages over measurement of just gravity alone:

- a. The gradient profiles have diagnostic properties, that, in many cases, make subsurface structure identification more straightforward.
- b. The gradients selectively filter out the effects of deeper-seated structures and enhance anomalies caused by

shallow structures of interest in geotechnical investigations.

Butler (1980a, b, c) discusses the measurement and application of gravity gradients.

38. Field procedures, data processing, and interpretation techniques for microgravimetric surveys are discussed in detail in Butler (1980a, d, and in press) and Butler et al. (in press); only a brief outline of these procedures and techniques will be presented here. Microgravimetric field procedures can be summarized as follows:

a. Establish survey grid or profile line and determine relative elevations at all grid stations.

b. Establish gravity base station.

c. Conduct gravity survey returning to the base station frequently (at least once per hour).

d. Correct gravity data in a timely manner while in the field so that questionable data can be discovered and the associated station reoccupied for another gravity measurement and so that the density of gravity stations in areas of interest can be increased.

39. The sequence of corrections applied to gravity measurements is as follows:

a. Correct for changes in gravity at the site as a function of time caused by earth-tide variations and gravity meter drift (drift correction).

b. Correct for variations in north-south positions of gravity stations (latitude correction).

c. Correction for elevation differences between stations (free-air and Bouguer corrections).

d. Correct for topographic variations around each gravity station.

e. Plot and contour the gravity data.

40. Although interpretation techniques vary greatly depending on the investigator as well as the objectives of the survey, the following will suffice for the present discussion:

a. Separate regional gravity components in the data from the local components; this is called the regional-residual separation.

b. Optionally generate processed gravity maps, such as derivative maps (Butler, in press) or upward/downward continuation maps (Grant and West, 1965).

c. Identify gravity anomalies.

d. Classify anomalies for qualitative interpretation or decide on a model for quantitative interpretation.

e. For quantitative interpretation, determine parameters of the model.

41. Considering the procedures and techniques identified in microgravity data acquisition, processing, and interpretation, the following list identifies specific steps which could facilitate and/or improve the microgravity method:

a. In item 37a, use of state-of-the-art electronic surveying systems for establishing survey grids and obtaining relative elevations could substantially reduce data reduction time for elevation surveys.

b. Develop computer algorithms for generating gravity station occupation schemes for given survey area size and shape and base station location; these schemes should optimally randomize possible errors over the gravity stations occupied between base station reoccupations, minimize walking distances, and include a desired 20 percent station reoccupation rate.

c. Develop computer programs for automatically correcting gravity data and producing Bouguer gravity contour maps.

d. Develop automated techniques for making the regional-residual separation and plotting residual gravity maps.

e. Develop automated techniques for generating processed gravity maps.

f. Develop procedures for identifying and classifying anomalies.

g. Develop efficient procedures for determining the parameters of structural models.

42. Only selected aspects of this "shopping list" can be addressed as part of the current effort; these aspects are briefly discussed, three computer programs developed as part of this effort are documented, and short selected examples of the use of the computer programs are presented. Finally, two more detailed examples will be presented which illustrate the use of the computer programs for processing and interpreting gravity data.

Gravity Station Occupation Schemes

43. In microgravity surveying, it is desirable to keep errors from all sources as low as possible; generally an accuracy of ± 5 μGal or better is desired in order that anomalies at the 10-μGal level can be detected (Butler, 1980a). The manner or sequence in which gravity stations are occupied during a survey can greatly influence the accuracy and overall quality of a microgravity survey. All stations that are occupied between successive reoccupations of the base station are referred to as a program. Each program should be planned to allow a base station reoccupation in less than one hour and to include gravity station reoccupations at an average rate of about 20 percent. Since the average time for acquiring gravity measurements in a microgravity survey is about 5 min per station, a program generally will consist of $\lesssim 10$ gravity readings, of which typically eight readings would be "first-time" station occupations and two readings would be station reoccupations.

44. Programs should be designed to occupy stations in a "zigzag" or "leap-frog" fashion in order to distribute random errors and to prevent any cumulative errors from combining to produce fictitious anomalies or elongated anomalies such as can result from long, continuous programs of station occupations (Butler, 1980a).* Figure 19 is a plan of the gravity stations for the Manatee Springs site microgravity survey, showing several typical programs. Clearly, the station occupation scheme shown in Figure 19 is not optimum, although errors will be properly randomized. An optimally generated occupation scheme should have approximately equal walking distances between each station in the program, including the base station at the beginning and end of a program. Optimal station occupation schemes are considered an important aspect of microgravity surveying, and work will continue toward finding expeditious manual or computer-aided methods for generating occupation schemes.

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* Personal communication, 1979, R. Neumann, Compagnie Generale de Geophysique, Massy, France.

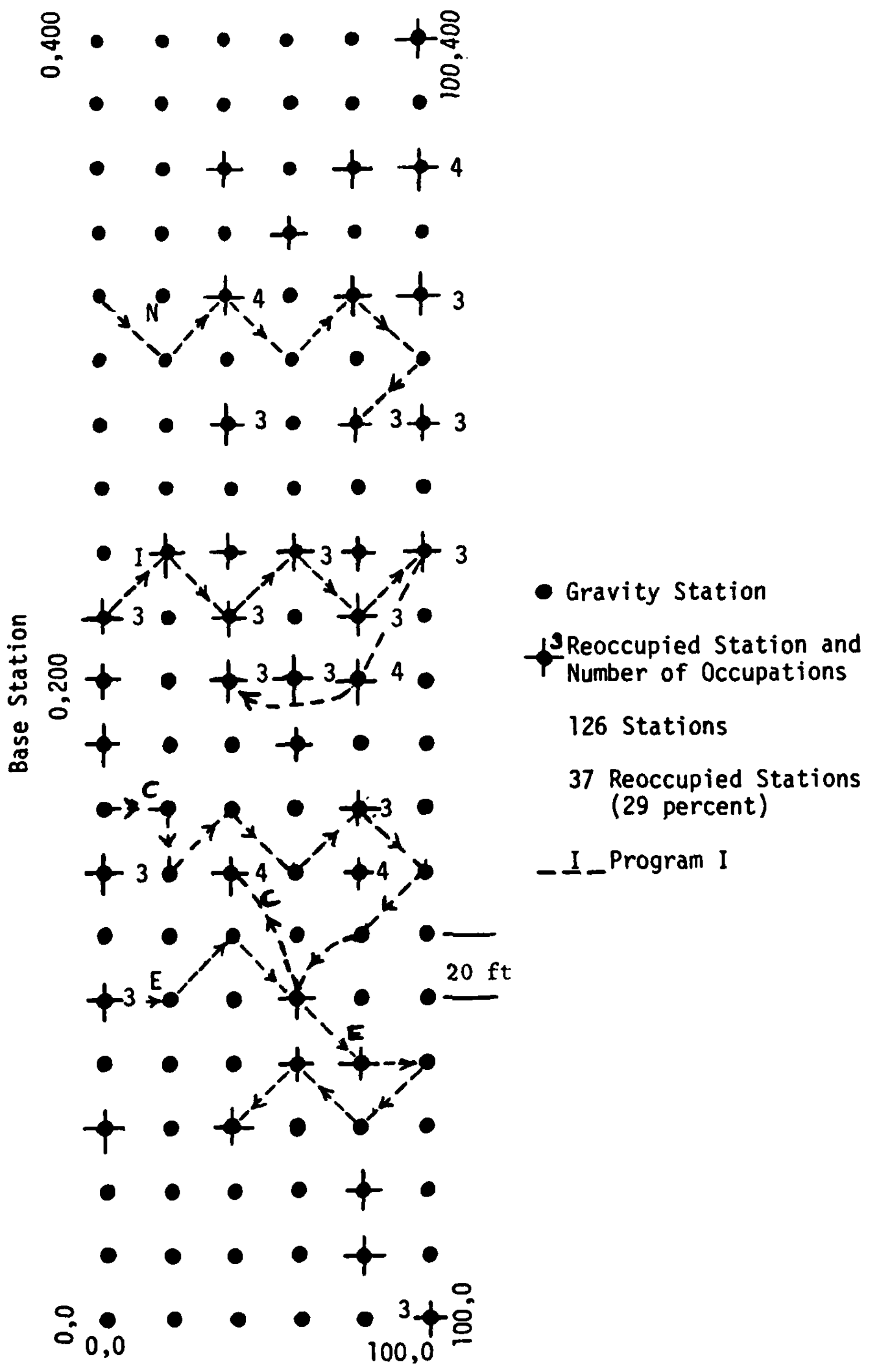


Figure 19. Gravity station plan with illustration of selected programs (All programs can be considered to begin and end with the base station (0,200).)

Use of Theoretical and Measured Earth-Tide Records

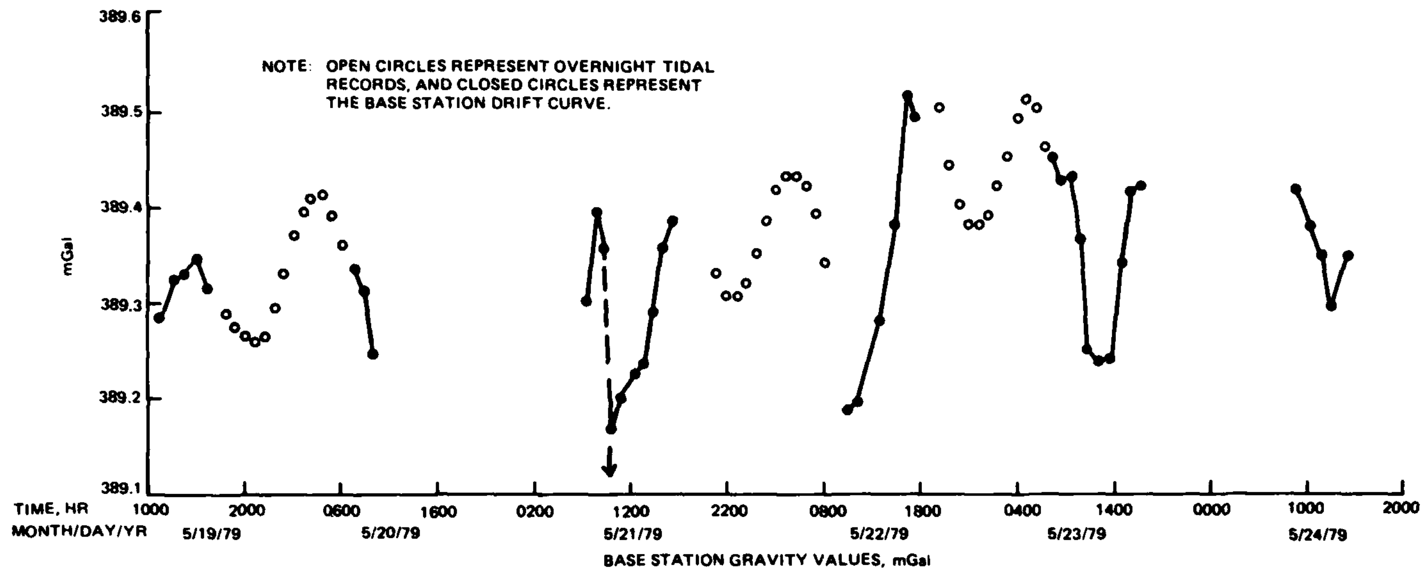
45. Reoccupations of the base station during a microgravity survey are used to construct a survey drift curve. The drift curve, which includes components due to both earth tides and instrument drift, is used to correct measurement values at all stations in the survey grid for time variations of the gravity values. It is assumed that the time variation observed at the base station is the same at all stations. Generally, the drift curve will consist of the earth-tide component, which can actually be calculated theoretically for a given site, a long-term cumulative instrument drift component, and a noncumulative instrument "drift" component, which can be caused, for example, by "rough handling" of the gravity meter. Frequent base station reoccupations coupled with the use of theoretical and measured tidal curves can be of great value in assessing the magnitudes of these components of the drift curve, for assuring the consistency of gravimeter performance during the survey, and for improving the overall accuracy of microgravity surveys.

46. Figure 20 is an example of the use of measured and theoretical earth/gravity tide records in conjunction with the field drift curve for the microgravity survey at the Medford Cave site. Since the overnight tidal records were recorded in a different location (i.e., a local motel room), the segments have been shifted vertically to best fit the base station curve. The phase of the two sets of data agrees quite well, but the amplitude variations of the field curve are more extreme. The arrow marks a base station reading just after an accidental jolt to the gravity meter; because of the frequent base station reoccupations, the recovery period after the jolt is adequately defined.

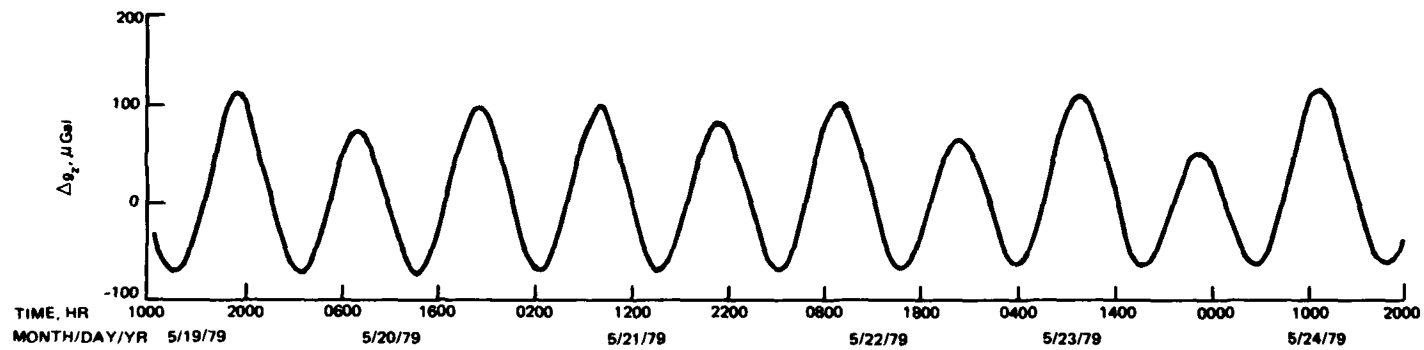
47. The theoretical curve in Figure 20 was produced by the program TIDES, which is described later in this Part. There is approximate-17 a 4-hr phase difference between the theoretical and measured tidal curves; such phase differences are not uncommon.* Discounting the phase

---

* An example is given later in this Part of a case where the phase agreement is nearly exact.



a. BASE STATION DRIFT CURVE FOR PART OF SITE MICROGRAVITY SURVEY WITH OVERNIGHT TIDAL RECORDS



b. THEORETICAL EARTH TIDE FOR SITE

Figure 20. Field base station drift curve and theoretical and observed earth/gravity tide records for the Medford Cave site microgravity survey

shift, there is good agreement between the amplitudes of the measured tidal curve (open circles, Figure 20a) and the theoretical tidal curve (Figure 20b). The long-term cumulative drift of the gravity meter appears to be about 2 μGal/hr, although there are nontidal meter drifts much larger than this which are not cumulative. Theoretical tidal curves can be produced prior to conducting field work to indicate the nature of the tidal variation to be expected at a given site during a given time frame.

TIDES: A Computer Program for Computing the Theoretical Earth Gravity Tide

48. The tidal gravity variation at a point on the surface depends primarily on two factors: (a) variation in gravitational attraction due to varying positions on the sun and moon (and to a smaller extent the planets) with respect to the point; and (b) amplification of the magnitude predicted by (a) due to yielding of the solid earth in response to the varying attractive force, i.e., elevation of the point actually varies with time.

49. Using the equations of Longman (1959), it is possible to calculate the theoretical tidal effect at any point on the earth's surface. The equations include a compliance or gravimetric amplification factor to account for yielding. Comparison of theoretical and measured earth tide records can in principle yield a determination of this amplification factor for any location; typical values range from 1.138 to 1.240 (Garland, 1977). Observations of the earth tide can give information not only on gross earth structure but also on anomalous tidal yielding in areas of major faults or other significant tectonic features. TIDES, modified from an original program by Robert Jachens,* computes the theoretical earth tide for any location and any time interval. A program listing of TIDES is in Appendix E.

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* Personal communication, Robert Jachens, U. S. Geological Survey, Menlo Park, Calif.

Input data

50. All data are input in free-field format. Data input are explained as follows:

Input No. 1: NCOMP, MM

NCOMP--number of tidal input data sets
MM--time increment in minutes between tide value calculations

Input No. 2: SLATD, SLATM, SLONGD, SLONGM, SELEV, DATEM, DATED, DATEY, TIMEH, TIMEM

SLATD, SLATM--site latitude in degrees (SLATD) and decimal minutes (SLATM)

SLONGD, SLONGM--site longitude in degrees (SLONGD) and decimal minutes (SLONGM)

SELEV--site elevation in metres (MSL)

DATEM, DATED, DATEY--starting date for calculation in month (DATEM), day (DATED), and year (DATEY) form

TIMEH, TIMEM--starting time for calculation in hours (TIMEH) and minutes (TIMEM), Greenwich time (24-hr clock)

Input No. 3: NTOTAL

NTOTAL--total number of time increments to be calculated, i.e., the total length of the tidal record will be = MM x NTOTAL

Program output

51. Program output consists of a compressed listing of calculated tidal values and a plot of tide variation as a function of time. Since the number of values calculated in a tidal record may be very large, a compressed listing of just the tidal values separated by a short blank space in a continuous fashion is given; each value in the list is separated in time by MM-minutes. The calculated tidal values are referenced to a zero value and have the proper sign for algebraically adding to gravity survey values to correct for tidal variations if desired. Next, a plot of tidal variation versus time is generated using PLOT2 (see Appendix B).

Example

52. An example output plot from TIDES has already been discussed (Figure 20). As another example, Figure 21 compares theoretical and observed earth tides for Vicksburg, Miss., for a three-day period (16-18 May 1980). The phases of the two curves in Figure 21 agree quite well. Amplitudes of the minima and secondary maxima of the two curves agree closely; however, the primary maxima of the measured tidal curve are nominally 50 μGal larger than the corresponding maxima on the theoretical curve. There are two possible explanations for the amplitude differences: (a) a small portion of the amplitude difference could be due to using a compliance factor that is too small for the site (1.160 was used); and (b) the electronic output of the gravimeter is nonlinear relative to the null position (McConnell, Hearty, and Winter, 1974). Since the position of the tidal variation relative to the meter null position will vary because of the superimposed approximately 2 μGal/hr drift, the gravimeter tidal curve would require frequent nonlinearity calibrations if used for quantitative tidal variation studies. The vertical scale of the measured curve was generated about the actual output position at 1930 hr on 18 May. At this time, drift has carried the tidal variation curve to within about 120 μGal of saturation of the electronic output on one side of the null position. The three events superimposed on the tidal record on 18 May in Figure 21 are earthquakes and illustrate an interesting application of the microgravimeter as a long-period vertical seismometer. Monitoring gravimeter tidal variation overnight during field surveys for the occurrence of large earthquakes will alert field parties as to the source of larger than normal background noise, since large earthquakes will produce noise levels as large as 100 to 200 μGals over a several hour period (Butler, 1980a).

Polynomial Surface-Fitting for Regional-Residual Separation

53. A polynomial surface-fitting procedure for determining regional fields is presented by Coons, Wooland, and Hershey (1967) for large-scale gravity surveys. This procedure was applied to the Manatee

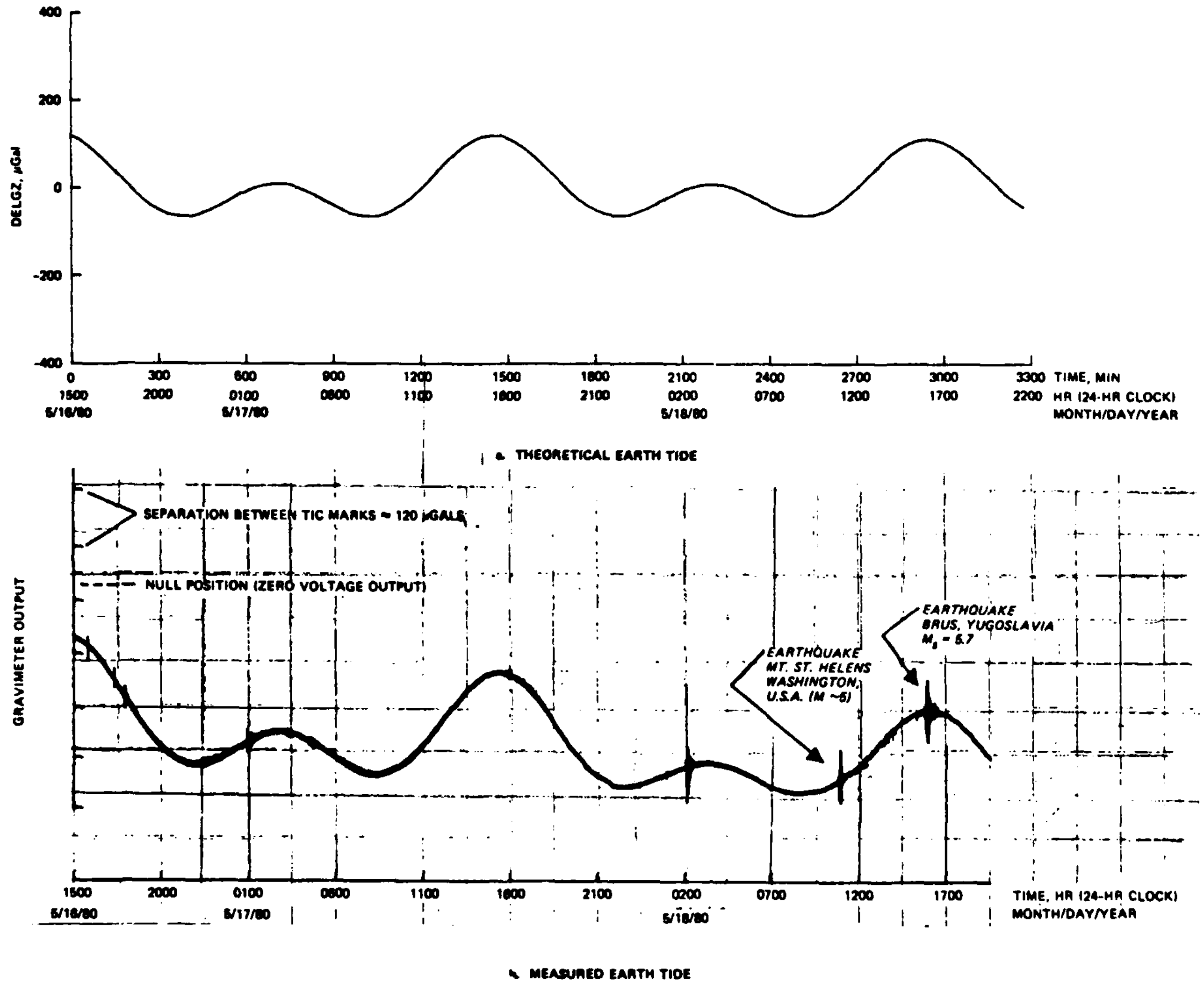


Figure 21. Comparison of theoretical earth tide and earth tide measured with Model-D gravimeter at Vicksburg, Miss., for three-day period

Springs microgravity survey data in order to determine its applicability to small-scale surveys. Figure 22 is a Bouguer anomaly (Butler, 1980a)* contour map for the survey. The surface-fitting procedure determines best-fitting polynomial surfaces of various orders to the Bouguer data. The basic concept is that, as successively higher order polynomial fits are subtracted from the Bouguer values, the residual anomaly values correspond to successively shallower structures (Coons, Wooland, and Hershey, 1967; and Butler, Whitten, and Smith, in press). Figure 23 shows first- through fourth-order fits to the Bouguer anomaly values. The polynomial surface fits were generated by a minicomputer using a general purpose, BASIC-language, polynomial regression program. The residual values are a direct output from the program.

54. Comparing the fits in Figure 23 to the Bouguer anomaly map in Figure 21 reveals that successively smaller scale features of the Bouguer map are reflected by the higher order fits, as expected. Clearly, the second-order fit in Figure 23 reflects the effects of a local structure; therefore, the first-order surface is selected as the appropriate regional. Figure 24 is the first-order residual anomaly map, where the approximate location of the known cavity system is indicated for comparison. The second-order fit in Figure 23 apparently indicates the primary gravity effect of the known cavity system; subtracting this second-order fit from the Bouguer anomaly map results in the second-order residual anomaly map in Figure 25. The second-order residual map primarily reflects anomalies caused by features shallower than the main cavity system; the small anomaly indicated by the arrow in Figure 24 corresponds to a vertical solution pipe extending nearly to the surface (discovered when a drill rig wheel broke through a surface soil bridge).

* The Bouguer gravity anomaly represents gravity survey data which have been corrected for instrument drift, tidal variation, latitude differences between survey stations, and elevation differences between stations (includes the free-air and Bouguer corrections) and between each station and surrounding terrain features (terrain correction).

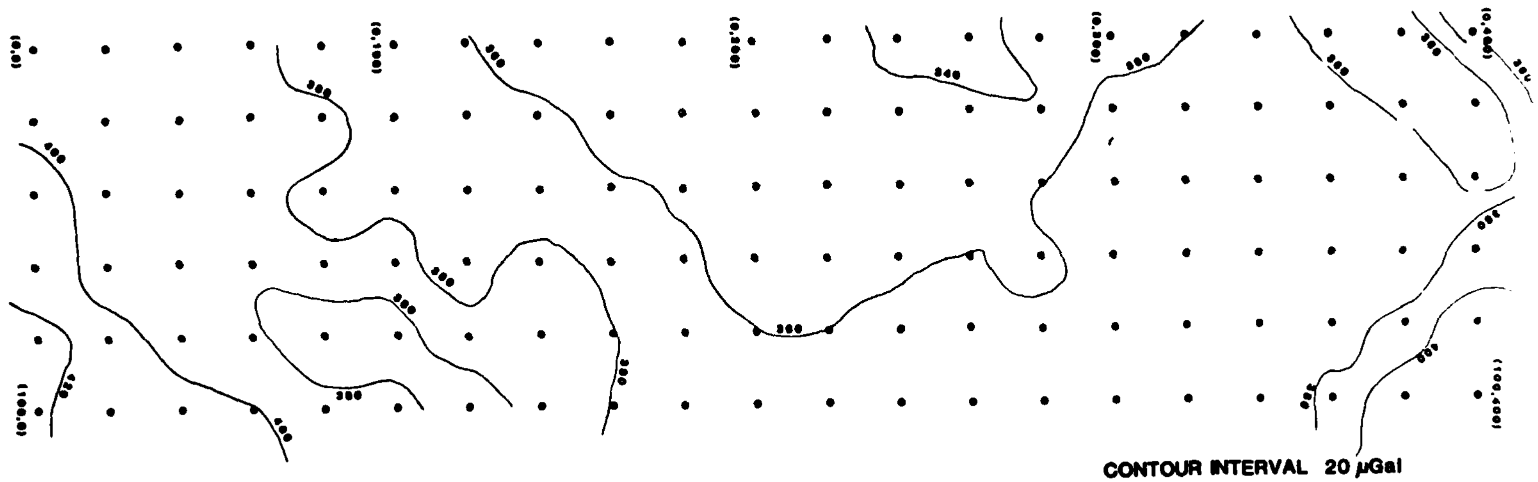


Figure 22. Bouguer gravity anomaly map, Manatee Springs site

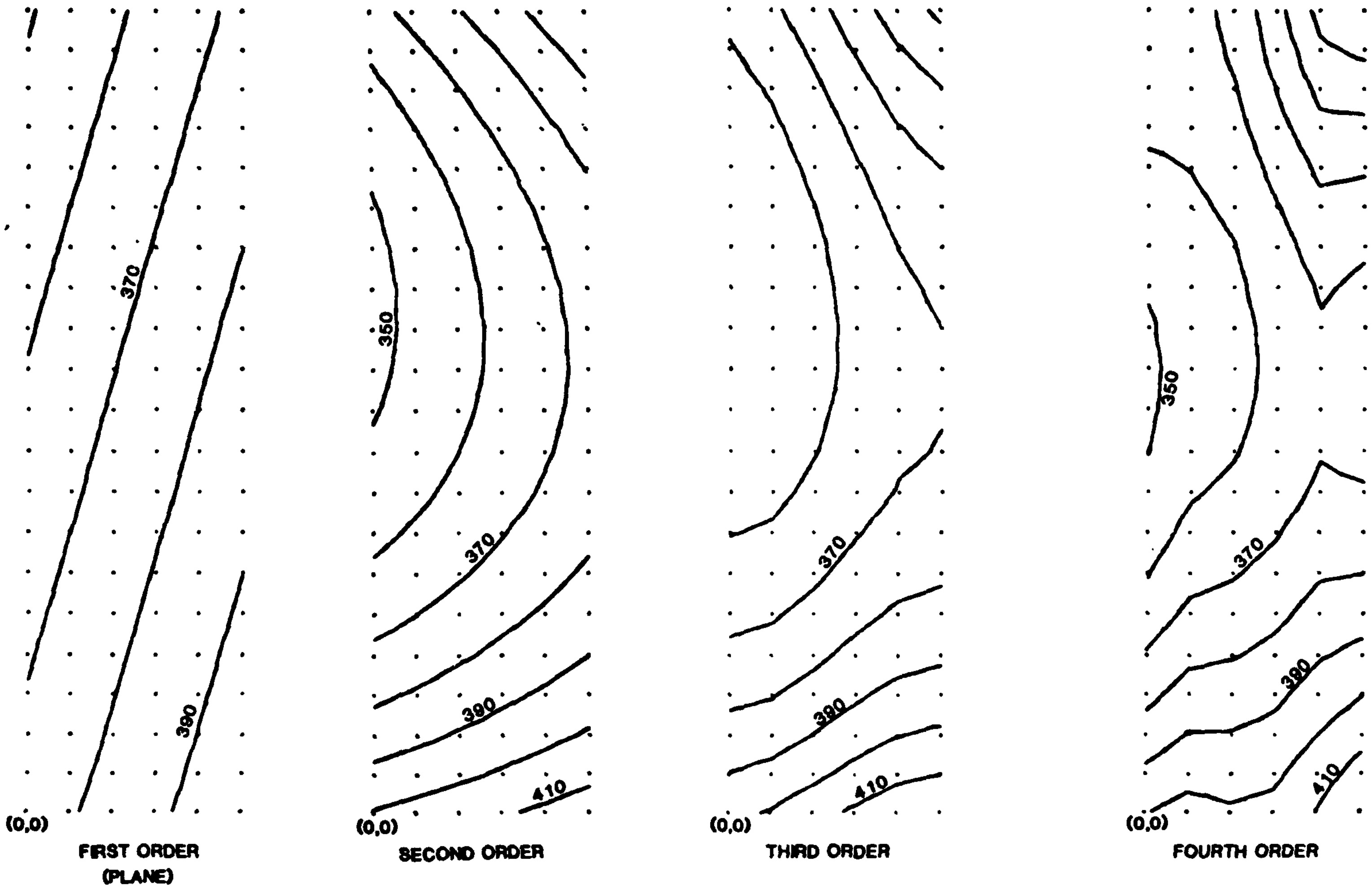


Figure 23. First- through fourth-order polynomial surface fits to the Bouguer gravity data (see Figure 13), contour interval = 10 μGal

Figure 24. First-order residual gravity anomaly map

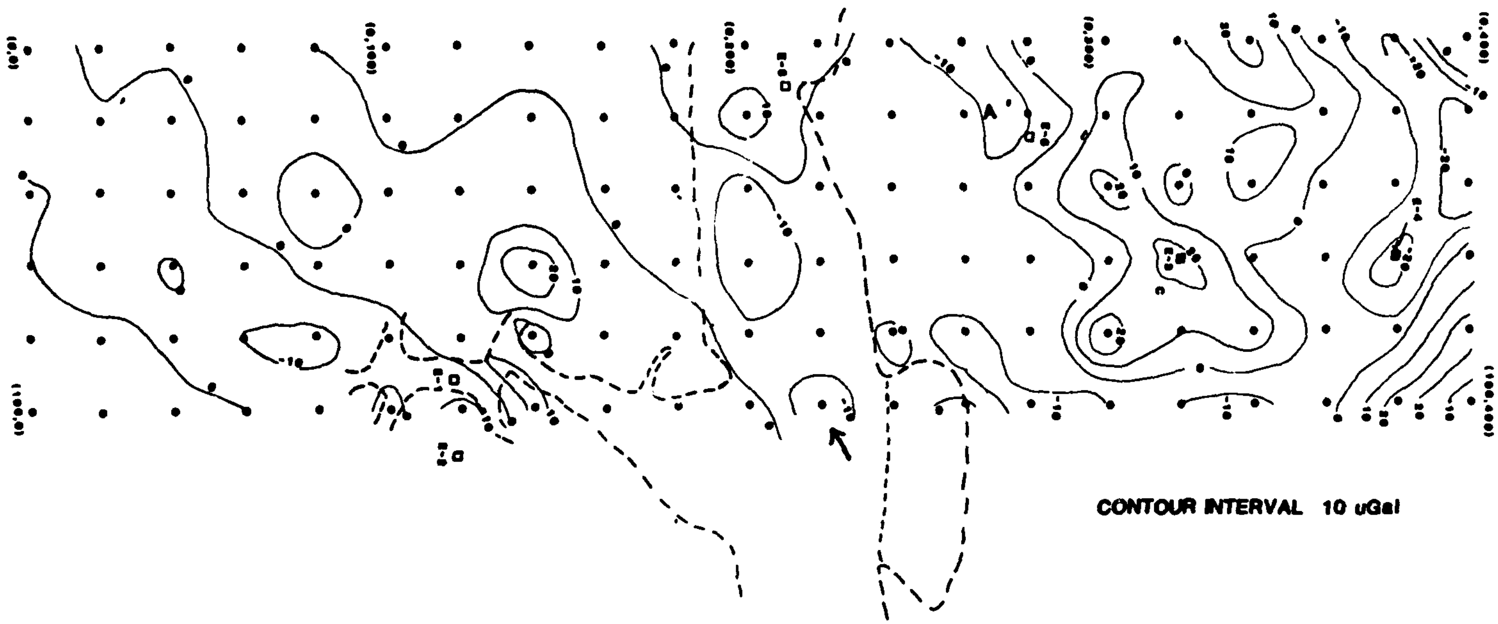


Figure 25. Second-order residual gravity anomaly map

Gravity Interpretation by Two-Dimensional Polygonal Cross-Section Models

55. A common procedure for gravity interpretation is to postulate a model which is consistent with the general features of the observed gravity field, calculate the gravity anomaly for that model, and compare it to the observed gravity anomaly field. If the gravity field of the model is geologically reasonable, then the model can be taken as a possible interpretation of the gravity anomaly (Butler, 1980a). Many geologic structures can be considered approximately two-dimensional, i.e., horizontal with constant cross section and constant strike, e.g., faults, block-faulted basins, synclines, anticlines, buried river valleys, cavity systems, etc. The two-dimensional approximation is generally adequate when the strike length is greater than four to six times all other dimensions of the structure including the depth. Talwani et al. (1959) developed an efficient algorithm for computing the graviational effect of two-dimensional polygonal cross section models using the line integral method of Hubbert (1948). Most two-dimensional structures can be adequately approximated in cross section by polygons with a small number of sides (<10 generally). In the case of a horizontal circular cylinder model, for example, which is inscribed by a polygonal approximation, the following table lists the ratio of the maximum value of the polygonal model gravitational effect (g_{zM}) to the exact value for the cylinder g_{zE} :

Number of Sides of Model	g_{zM}/g_{zE}
4	0.64
8	0.90
16	0.98

56. The computer program TALGRAD was written to compute gravity as well as gravity-gradient profiles across arbitrary, polygonal cross-section models using the Talwani algorithm. This program has

proven extremely useful for predicting the gravity anomalies to be expected from various known or postulated structures as well as for interpreting gravity data in an iterative fashion. Figure 25 is an example of the use of TALGRAD to compute the gravity anomaly to be expected from the main cavity at the Manatee Springs site (using approximate depths and cross-section dimensions from cave diver reports). TALGRAD as well as further examples of its use will be discussed later in this Part.

TALGRAD: A Computer Program for Computing Gravity and Gravity-Gradient Profiles Over Two-Dimensional Models

57. TALGRAD uses the procedure developed by Hubbert (1948) and Talwani et al. (1959) to compute gravity and gravity-gradient profiles over two-dimensional models. Actually, gravity profiles are computed on the surface (z = 0) and at selected elevations above the surface (z = -DELZ, -2 DELZ, ..., -SMAX) at discrete profile points (separated by DELX). The vertical and horizontal gradients are then calculated as finite differences or interval gradients. A listing of TALGRAD is given in Appendix F.

Input data

58. All input is in free-field format and the program will call for the input variables by name. All length dimensions must be consistent; either kft (1000's of ft) or m are acceptable. The density contrast must be in g/cm^3. Input data are explained as follows:

Input No. 1: K, DELX, DELZ, ZMAX

K--number of profile stations
DELX--distance between stations
DELZ--vertical distance between elevations at which gravity is computed at each profile station
ZMAX--maximum elevation at which gravity is computed (ZMAX is an integral multiple of DELZ)

Input No. 2: NPOLY

NPOLY--number of closed polygons comprising the model

Input No. 3:

Dimensions in kft (enter 1) or metres (enter 2)

Input No. 4: DELRO, N

DELRO--density contrast for a polygon
N--number of corners in a polygon

Input No. 5: X1, Z1, X2, Z2, ..., XN, ZN

X,Z--coordinate pairs for polygon corners, N-pairs to be input in clockwise order

(The preceding two input sequences, No. 4 and 5, will be repeated once for each polygon. Also these two input sequences are repeated for each elevation in the calculation.)

Input No. 6:

Option to calculate gravity gradients (enter 1) or not (enter 2) and program execution will terminate.

Input No. 7: DELXX, DELZZ

DELXX, DELZZ--intervals to be used for horizontal and vertical gradient calculations in increments of DELX and DELZ, respectively

Input No. 8: HZ

HZ--elevation for which the horizontal gradient profile is desired, in increments of DELZ (=0 to calculate profile on the surface z = 0)

Input No. 9:

Option to recalculate gradients for different values of DELXX and DELZZ--Yes, enter 1; No, enter 2

Program output

59. Both tabular listings and plots are produced by the program, and many of the lists and plots are optional. The output sequence is described below:

a. Following Inputs 4 and 5 for each polygon, a listing summarizes all the input data for that polygon.

b. An optional listing of the results of the gravity profile calculation is generated for elevation 0.

c. An optional plot of the gravity profile for elevation 0 is produced.

d. Optional listings and plots are produced for each additional elevation in the calculation.

e. A listing of the vertical gradient profile calculations is generated.

f. A plot of the vertical gradient profile is produced.

g. A listing of the horizontal gradient profile calculations is generated.

h. A plot of the horizontal gradient profile is produced, where the value is plotted at the midpoint of the horizontal interval DELXX.

i. An optional gradient space plot is produced (i.e., $g_{z,x}$ versus $g_{z,z}$).

j. An optional plot of the square of the modulus $(a^2(x))$ of the analytic signal is produced, where $a^2(x) = g^2_{z,z}(x) + g^2_{z,x}(x)$.

k. The entire sequence of output from item e to j can be repeated with different values of DELXX and DELZZ, if desired.

Examples

60. Example 1. Figure 26 is an example of the use of TALGRAD to compute the gravity profile over a model of the Manatee Springs main

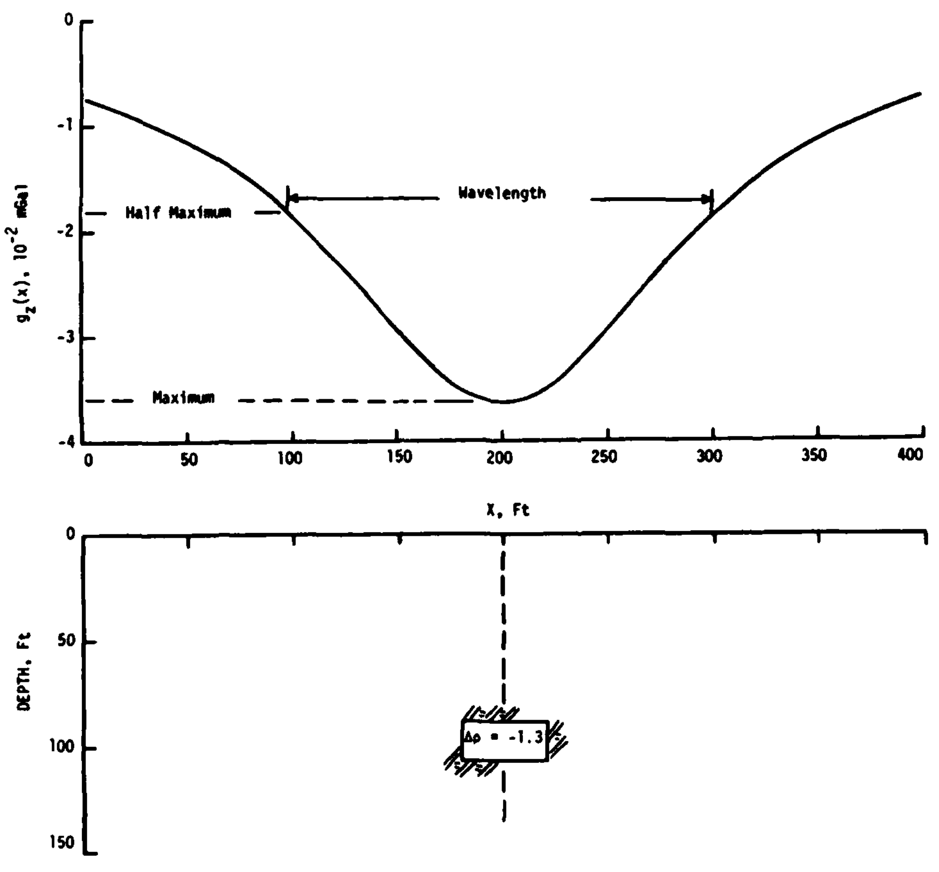


Figure 26. Two-dimensional model of the main cavity at the Manatee Springs site and a gravity profile computed by TALGRAD

cavity; a complete listing of the input data and output listings for this example is given in Figure 27.

61. Example 2. Fugro National, Inc. (1980) and McLamore and Walen (1979) report the results of an extensive gravity survey in and around Dry Lake Valley, Nev., in the Basin and Range Province. Using the three-dimensional gravity inversion computer program of Cordell (1970), the gravity data were inverted to yield a three-dimensional model of the subsurface. For the inversion, a constant density contrast (of $-0.45\ g/cm^3$) was used. Figure 28 shows the residual gravity anomaly map, and Figure 29 shows depth to basement rock contours from the three-dimensional inversion. A section view model along profile AA′ is given in Figure 30. Since block faulting is the predominant structural style of the area, the interpretation is reasonable. As an example of the use of TALGRAD, gravity and gravity-gradient profiles along AA′ were computed from the model in Figure 30. The gravity profile, the horizontal and vertical gravity-gradient profiles, a gradient space plot, and a plot of the square of the modulus of the analytic signal are shown in Figures 31-34, respectively. Selected data from the three-dimensional inversion results are shown in Figure 31 for comparison. This example will be considered in greater detail later in this Part.

Determination of Vertical Gravity-Gradient Profiles by a Hilbert Transform Procedure

62. Butler (1980a, b) suggests a procedure by which structural model parameters can be determined by a simultaneous analysis of both the vertical and horizontal gravity-gradient profiles across a structure. Except for shallow structures (<10 to 15 m depth), the use of a short tripod and "microgal" gravimeter to determine interval vertical gradients does not appear practical due to high levels of "gradient noise" caused by very shallow density variations. The vertical gradient profile can, however, be calculated from the horizontal gradient profile if the source of the gravity anomaly is approximately two-dimensional. This relation is expressed

```
K,DELX,DELZ,ZMAX
=41,.01,0,0
NPOLY
=1
DIMENSION IN KFT(TYPE 1) OR METERS(TYPE 2)?
=1
POLYGON-- 1
DELRO,N
=-1.3,4
X1,Z1,.....XN,ZN
=.18,.088,.22,.088,.22,.1056,.13,.1056


                         STATIONS     POLYG. SIDES       DENSITY
                            41            4             -1.300000

                    VERTEX         DISTANCE                DEPTH
                       1            0.180000              0.088000
                       2            0.220000              0.088000
                       3            0.220000              0.105600
                       4            0.180000              0.105600
DO YOU WANT TO PRINT GZ FOR H=  0.   --YES(1),NO(2)
=1


-----ELEVATION =    0.        -----

               STATION          X              GZ(X)

                  1          0.              -0.007334
                  2          0.010000        -0.007965
                  3          0.020000        -0.008673
                  4          0.030000        -0.009448
                  5          0.040000        -0.010344
                  6          0.050000        -0.011375
                  7          0.060000        -0.012516
                  8          0.070000        -0.013865
                  9          0.080000        -0.015255
                 10          0.090000        -0.016847
                 11          0.100000        -0.018710
                 12          0.110000        -0.020731
                 13          0.120000        -0.022941
                 14          0.130000        -0.025319
                 15          0.140000        -0.027905
                 16          0.150000        -0.030363
                 17          0.160000        -0.03270
                 18          0.170000        -0.034644
                 19          0.180000        -0.036541
                 20          0.190000        -0.037637
```

Figure 27. TALGRAD input/output for the example in Figure 25; user input indicated by an '=' sign (Continued)

21	0.200000	-0.037616
22	0.210000	-0.036737
23	0.220000	-0.035541
24	0.230000	-0.034344
25	0.240000	-0.032709
26	0.250000	-0.030313
27	0.260000	-0.027902
28	0.270000	-0.025318
29	0.280000	-0.02294-
30	0.290000	-0.020731
31	0.300000	-0.018710
32	0.310000	-0.016897
33	0.320000	-0.015255
34	0.330000	-0.013803
35	0.340000	-0.012516
36	0.350000	-0.011375
37	0.360000	-0.010364
38	0.370000	-0.009469
39	0.380000	-0.008673
40	0.390000	-0.007965
41	0.400000	-0.007334

```
DO YOU WANT PLOTS OF GRAVITY PROFILES?--YES(1), NO(2)
=1
PLOT GRAVITY PROFILE FOR H=  0.
READ X0,Y0,SFX,SFY,IA,IDASH,THETA
=1,5,50,.001991,0,0,0
READ HTX,XL,XS,NDX,NPX,SPX,ITX
=.1,8,0,0,0,0,0
READ HTY,YL,YS,NDY,NPY,SPY,ITY
=.1,4,-4,0,-2,0,0
READ X-LABEL
=X, FT
READ Y-LABEL
=GZ(X), MGAL
4
DO YOU WANT TO CALCULATE GRAVITY GRADIENT?  TYPE 1 FOR YES, 2 FOR NO
=2
```

Input specifications for producing the gravity profile plot in Figure 25.

Figure 27. (Concluded)

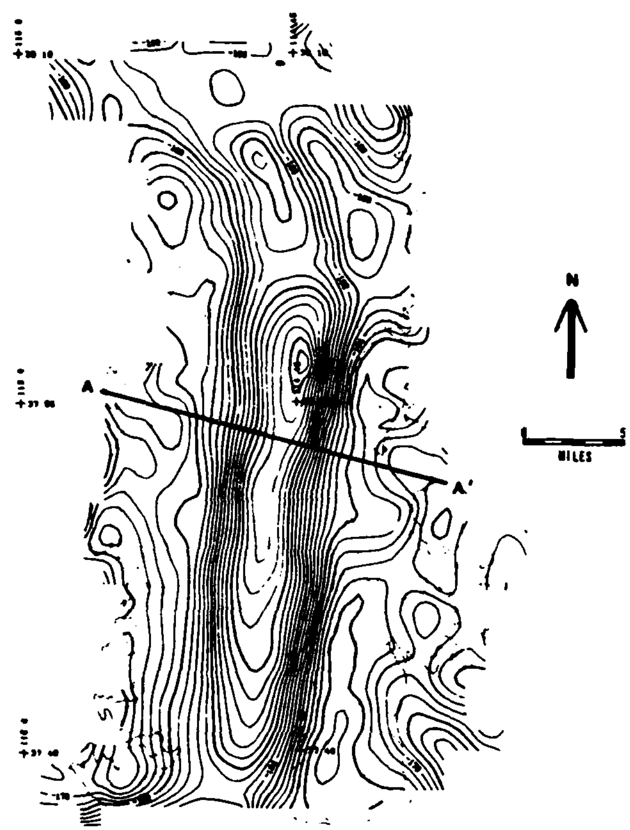


Figure 28. Dry lake valley residual anomaly contours

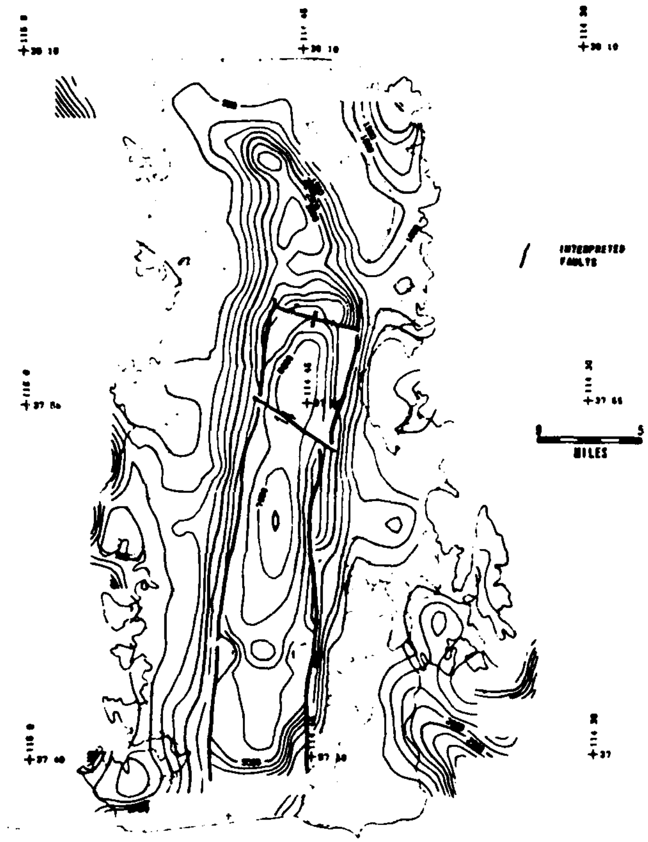


Figure 29. Dry lake valley bedrock depth contours

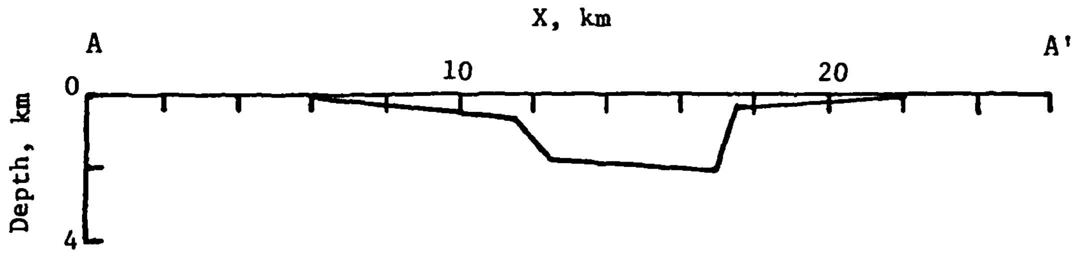


Figure 30. Structure model from 3D gravity inversion

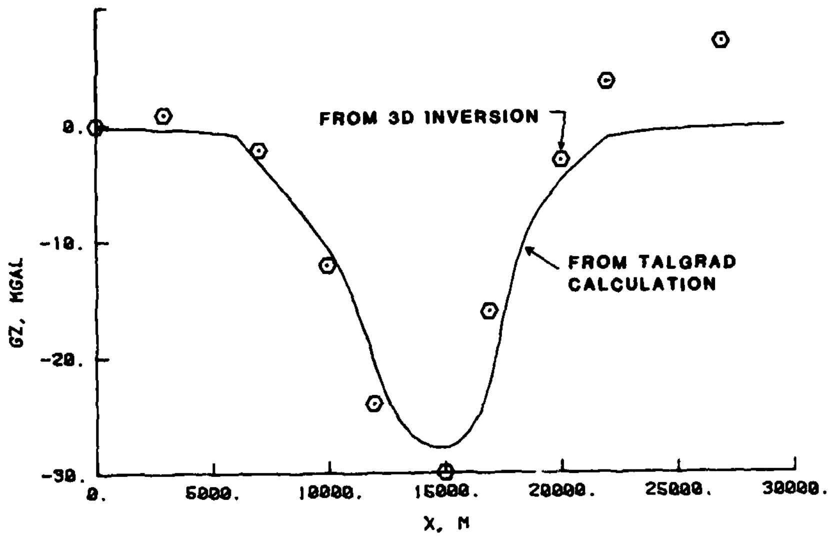


Figure 31. Comparison of gravity profile along AA′ from TALGRAD calculation using the model in Figure 30 with the results of a 3D gravity inversion

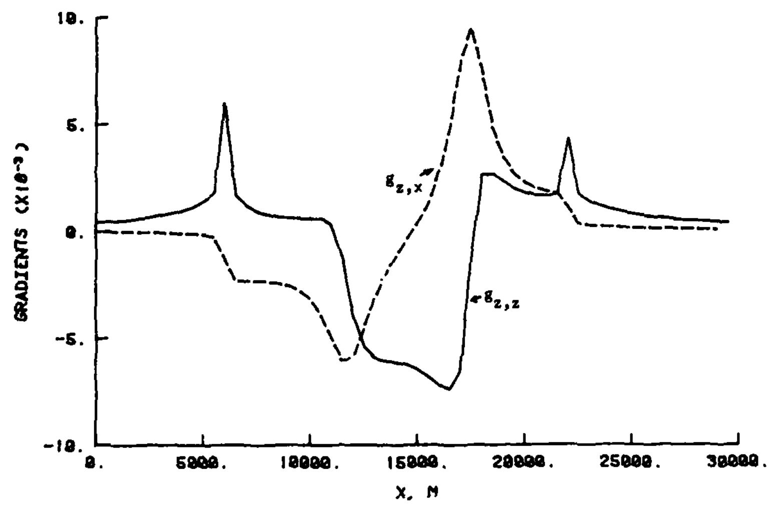


Figure 32. Gravity-gradient profiles along AA′ calculated by TALGRAD using model in Figure 30

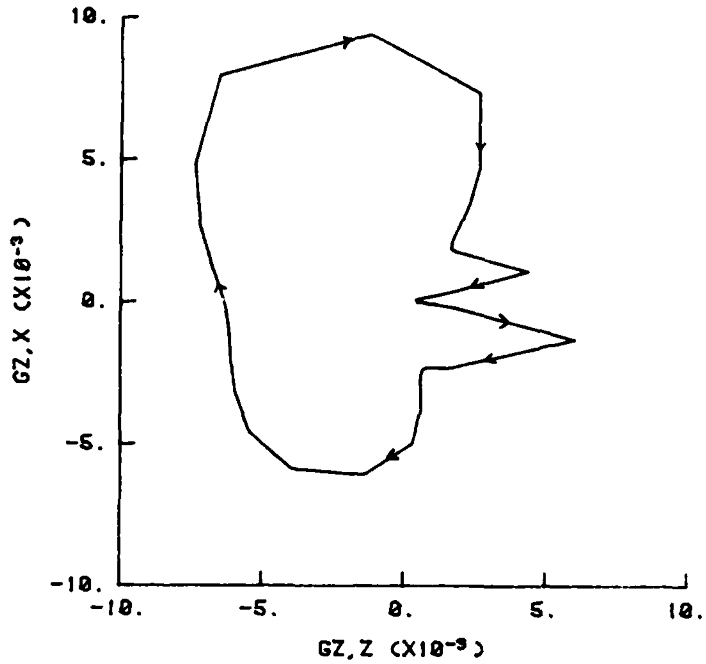


Figure 33. Gradient space plot along AA′ using gradient profiles in Figure 32

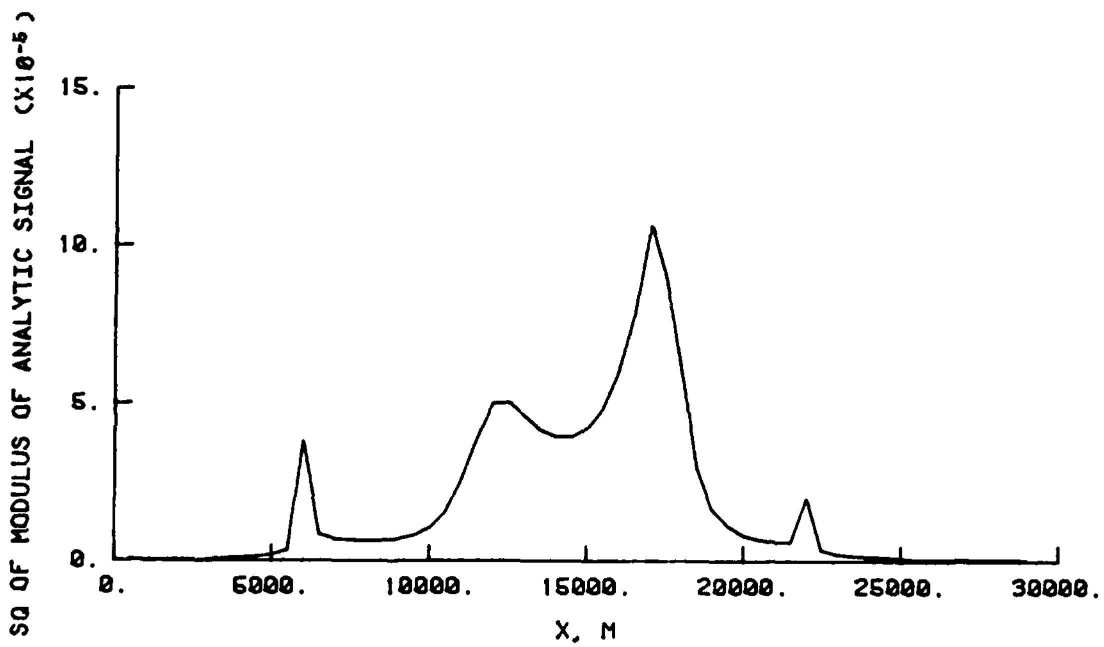


Figure 34. Square of modulus of analytic signal plot along AA′

$$g_{z,z}(x) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{g_{z,x}(\zeta)}{\zeta - x} \, d\zeta \qquad (2)$$

where x is the profile point at which the vertical gradient is to be evaluated, $g_{z,z}$* is the vertical gradient, $g_{z,x}$* is the horizontal gradient, and the integral is to be interpreted in terms of its Cauchy principal value.**

63. The program HILBERT was written, using an algorithm suggested by Shuey (1972), to compute the discrete Hilbert transform of a set of discrete profile data. The program as well as examples of its use will be discussed later in this Part.

HILBERT: A Computer Program for Computing the Discrete Hilbert Transform of Profile Data

Discrete Hilbert transform algorithm

64. The Hilbert transform relation between a continuous profile function $f(x)$ and a continuous transformed profile function $q(x)$ is

$$q(x) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{f(\beta)}{\beta - x} \, d\beta$$

$$\equiv f_h(x) = H(f(x)) \qquad (3)$$

Now let $f(x)$ be a discrete set of uniformly spaced data, and approximate the data by a parabola centered on the singularity of the integrand

---

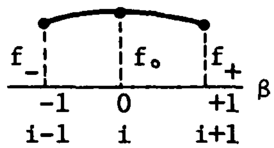
* $g_{z,z} \equiv \partial g_z/\partial z$ and $g_{z,x} \equiv \partial g_z/\partial x$, where g_z is the vertical component of the gravitational acceleration (z-axis downward)

** I.e., the integral is interpreted in the sense

$$\lim_{a \to 0} \left(\int_{-\infty}^{x-a} + \int_{x+a}^{\infty} \right) \frac{g_{z,x}(\zeta)}{\zeta - x} \, d\zeta$$

β=x (passing through β and the two adjacent points) and with a linear fit to all other pairs of points in the profile data. Using this approximation to the discrete set of profile data, Equation 3 can be numerically integrated in a straightforward manner.

65. The diagram below defines the terminology for considering the parabolic fit centered on the singularity.



66. For simplicity in the derivation, a unit digitizing interval is used and the singularity is taken to be at $\beta=0$ at the i^{th} data point. The parabolic fit to $f(\beta)$ is defined as follows:

$$f(\beta) = a + b\beta + C\beta^2 \tag{4}$$

$$\left.\begin{aligned} f(o) &= f_o = a \\ f(+1) &= f_1 = a + b + c \\ f(-1) &= f_{-1} = a - b + c \end{aligned}\right\} \tag{5}$$

Equation 5 can be solved for the empirical constants in Equation 4 as follows

$$a = f_o$$

$$b = \frac{f_1 - f_{-1}}{2}$$

$$c = \frac{f_1 - f_{-1}}{2} - f_o$$

and Equation 2 can be written

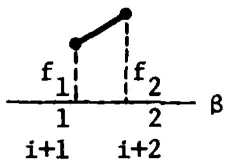
$$f(\beta) = f_o + \left(\frac{f_1 - f_{-1}}{2}\right)\beta + \left(\frac{f_1 + f_{-1}}{2} - f_o\right)\beta^2 \tag{6}$$

Equation 6 can now be substituted into Equation 3 to find the contribution to the integral from the parabolic fit centered on the singularity

$$\frac{1}{\pi}\int_{-1}^{1} \frac{f(\beta)}{\beta}\, d\beta = \frac{1}{\pi}\left[f_o \ln|\beta| + \left(\frac{f_1 - f_{-1}}{2}\right)\beta + \frac{1}{2}\left(\frac{f_1 + f_{-1}}{2} - f_o\right)\beta^2\right]_{-1}^{+1}$$

$$= \frac{1}{\pi}(f_1 - f_{-1}) \tag{7}$$

67. Examining the linear fit to the first two data points to the right of the singularity, as an example, yields



$$f(x) = a + bx$$

$$f_1 = a + b\beta_1$$

$$f_2 = a + b\beta_2$$

$$a = f_1 - b\beta_1$$

$$b = (f_2 - f_1)/(\beta_2 - \beta_1)$$

$$f(\beta) = f_1 + \left(\frac{f_2 - f_1}{\beta_2 - \beta_1}\right)(\beta - \beta_1)$$

$$= \frac{f_1\beta_2 - f_2\beta_1}{\beta_2 - \beta_1} + \frac{(f_2 - f_1)\beta}{\beta_2 - \beta_1}$$

$$= \frac{f_1(\beta - x) - f_2(\beta_1 - x)}{\beta_2 - \beta_1} + \frac{(f_2 - f_1)(\beta - x)}{\beta_2 - \beta_1} \tag{8}$$

Equation 8 can be substituted into Equation 2 to evaluate the form of one of the terms resulting from the successive linear fits to pairs of data points:

$$\frac{1}{\pi}\int_{\beta_1}^{\beta_2} \frac{f(\beta)}{\beta - x}\, d\beta = \frac{1}{\pi}\left[\frac{f_1(\beta_2 - x) - f_2(\beta_1 - x)}{\beta_2 - \beta_1}\,\ell n\left(\frac{\beta_2 - x}{\beta_1 - x}\right) + (f_2 - f_1)\right] \qquad (9)$$

If a unit digitizing interval is again assumed, $\beta_2 - \beta_1 = 1$.

68. The complete expression for the numerical evaluation of Equation 3 for a discrete set of profile data will be the sum of Equation 7 and a series of terms of the form of Equation 9 for all data pairs to the right and left of the singularity. Necessarily, in practice, the profile will be finite in length; this will cause no problem in regard to the limits of integration of Equation 3 if all values of $f(\beta)$ are zero beyond the ends of the profile, which can be simulated by adding a zero to each end of the discrete data set. If the profile is a "residual" profile which approaches zero at the ends of the data set, then the simple procedure of dropping the profile to zero outside the data will present no problems. Otherwise, a more elaborate extrapolation to zero beyond the data may be needed. If there are N data values in the set, shift the data one position to the right and add a zero at $n = 1$ and $n = N + 2$. Considering this revised data set, the result of summation of Equation 7 with all the terms of the form of the second term of Equation 9 is the value of $\frac{1}{\pi}(f_{N+2} - f_1)$ which is identically zero. Thus, remaining is a summation of terms of the form of the first term of Equation 9 involving data pairs to the right and left of the singularity (but not including the singularity itself). The result will be called the discrete Hilbert transform $H^D(f(x))$ or $f_H^D(x)$. The above procedure is repeated for all profile positions x.

Program input and output

69. The computer code HILBERT, listed in Appendix G, evaluates the discrete Hilbert transform using the algorithm discussed above.

Input to HILBERT consists of the number of data values N, the actual profile spacing between points DELX, and the profile values T. Output consists of a tabular listing of profile position X, profile data value T, discrete Hilbert transform H, the value $A(=T^2 + H^2)$, and plots of T versus X, H versus X, H versus T, and A versus X. In practice, T will generally be the horizontal gravity gradient (tabular column labeled GX,X) and H will be the computed vertical gravity gradient (tabular column labeled GZ,Z).

Example: a test of the discrete Hilbert transform algorithm

70. A procedure for testing the proposed algorithm for evaluating the discrete Hilbert transform can be formulated by examining the properties of the Hilbert transform. From the definition of convolution (denoted by *), Equation 2 can be expressed as:

$$f_H(x) = \left(-\frac{1}{\pi x}\right) * f(x) \tag{2}$$

Applying the convolution theorem gives:

$$F(f_H(x)) = i \operatorname{sgn}(s) F(f(x))$$

where F denotes the Fourier transform and s is the transform variable. Inverting this equation gives

$$\begin{aligned} F(f(x)) &= -i \operatorname{sgn}(s) F(f_H(x)) \\ f(x) &= \left(\frac{1}{\pi x}\right) * f_H(x) \\ &= -\left(-\frac{1}{\pi x}\right) * f_H(x) \\ &= -\left(\frac{1}{\pi}\right) \int_{-\infty}^{\infty} \frac{f_H(\beta)}{\beta - x}\, d\beta \end{aligned}$$

$$f(x) = -H(f_H(\beta)) \tag{10}$$

Equation 10 suggests the following test for the discrete Hilbert transform algorithm:

$$\text{if} \quad f_H^D(x) \simeq f_H(x) \ ,$$

$$\text{then} \ H^D(f_H^D(x)) \simeq - f^D(x) \tag{11}$$

where $f^D(s)$ denotes the discrete profile data set. That is, two successive applications of the discrete Hilbert transform to the profile data set should yield the negative of the original profile data set.

71. Consider the simple functional relation:

$$f(x) = \frac{1}{1 + x^2} \tag{12}$$

which has the analytic Hilbert transform (Erdelyi, 1954)

$$f_H(x) = \frac{-x}{1 + x^2} \tag{13}$$

Equation 12 is a symmetric function with half-width at half-maximum equal to 1.0, maximum value equal to 1.0 at x = 0, and asymptotes which approach 0 in both directions. As a first test, the function $f(x)$ is sampled or discretized at increments $\Delta x = 1$ over the range $-10 \leq x \leq 10$ and set equal to zero outside this range. Figure 35a contains the tabular output resulting from inputting $f^D(x)$, with $f_H^D(x)$ being the computed discrete Hilbert transform. In Figure 35b, $f_H^D(x)$ is the input data and $H^D(f_H^D(x))$ is the output (i.e., the output represents two successive Hilbert transform operations applied to $f^D(x)$) . Plots of $f^D(x)$, $f_H^D(x)$, and $H^D(f_H^D(x))$ are shown in Figure 36. Qualitatively, $H^D(f_H^D(x))$ can be recognized as the negative of $f^D(x)$; however, the maximum absolute value is 0.71 compared to 1.0 for $f^D(x)$, the half-width at half-maximum is 1.5 compared to 1.0 for $f^D(x)$, and the two ends of the calculated profile cross the x-axis while the $f^D(x)$ profile does not.

x	$f^D(x)$	$f_H^D(x)$
-10.0	0.00990	0.10598
-9.0	0.01219	0.11373
-8.0	0.01538	0.12621
-7.0	0.02000	0.14276
-6.0	0.02702	0.16485
-5.0	0.03846	0.19527
-4.0	0.05882	0.23911
-3.0	0.10000	0.30589
-2.0	0.20000	0.40823
-1.0	0.50000	0.44459
0	1.00000	0.00000
1.0	0.50000	-0.44459
2.0	0.20000	-0.40823
3.0	0.10000	-0.30589
4.0	0.05882	-0.23911
5.0	0.03846	-0.19527
6.0	0.02702	-0.16485
7.0	0.02000	-0.14276
8.0	0.01538	-0.12621
9.0	0.01219	-0.11373
10.0	0.00990	-0.10598

Figure 35a. Discrete Hilbert transform f_H^D of f^D

x	$f_H^D(x)$	$H^D(f_H^D(x))$
-10.0	0.10598	0.11857
-9.0	0.11373	0.07730
-8.0	0.12621	0.06254
-7.0	0.14276	0.05120
-6.0	0.16485	0.03959
-5.0	0.19527	0.02453
-4.0	0.23911	0.00029
-3.0	0.30589	-0.04874
-2.0	0.40823	-0.18225
-1.0	0.44459	-0.49781
0	0.00000	-0.71351
1.0	-0.44459	-0.49781
2.0	-0.40823	-0.18225
3.0	-0.30589	-0.04874
4.0	-0.23911	0.00029
5.0	-0.19527	0.02453
6.0	-0.16485	0.03959
7.0	-0.142765	0.05120
8.0	-0.12621	0.06254
9.0	-0.11373	0.07730
10.0	-0.10598	0.11857

Figure 35b. Discrete Hilbert transform H^D of f_H^D

Figure 35. Tabular output from HILBERT for test case with $\Delta x = 1$ and $-10 \leq x \leq 10$

72. To illustrate the effects of data spacing Δx and profile length, several additional tests were conducted using the same function $f(x)$. Firue 37 shows plots of $f^D(x)$, $f_H^D(x)$, and $H^D(f_H^D(x))$ for $\Delta x = 0.5$ and the same profile length as in the previous test. The maximum absolute value for $H^D(f_H^D(x))$ is now 0.86 compared to 0.71 for the previous test case and to 1.0 for $f^D(x)$. Also, the half-width at half-maximum is 1.05, very close to the value for $f^D(x)$. The behavior of the ends of the $H^D(f_H^D(x))$ profile is similar in both test cases.

73. For another test case, the data spacing is the same as the first test $\Delta x = 1$, but the profile length is doubled $(-20 \leq x \leq 20)$. The maximum absolute value of $H^D(f_H^D(x))$ is 0.74 and half-width at half-maximum is 1.45. The results for this case are shown in Figure 38. The primary effect of doubling the profile length compared to the first test case is to reduce the distortion near the ends of the profile line.

74. Significant features of the above three test cases as well as three additional ones are summarized in the following tabulation:

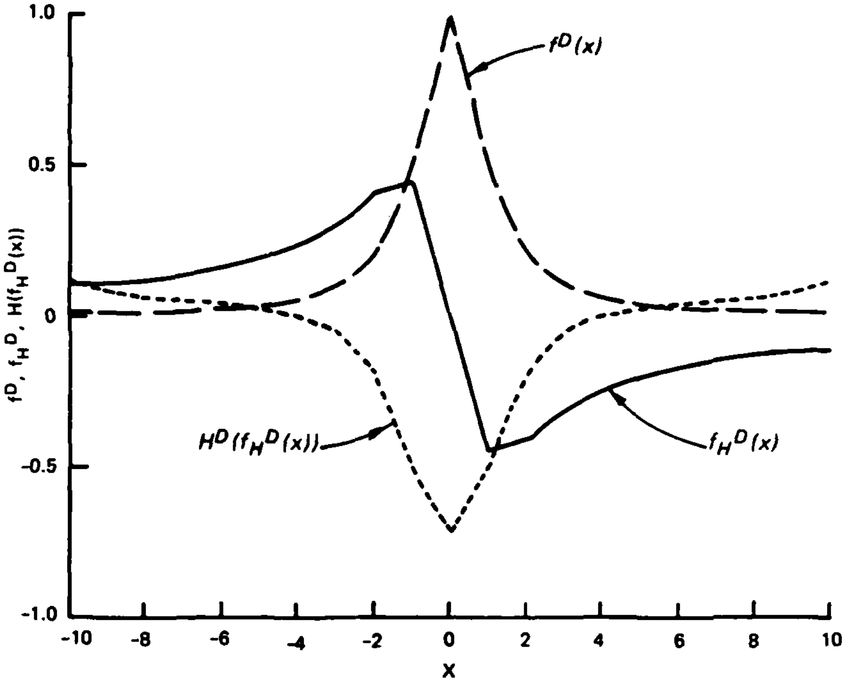


Figure 36. HILBERT test case for $\Delta x = 1$ and $-10 \leq x \leq 10$

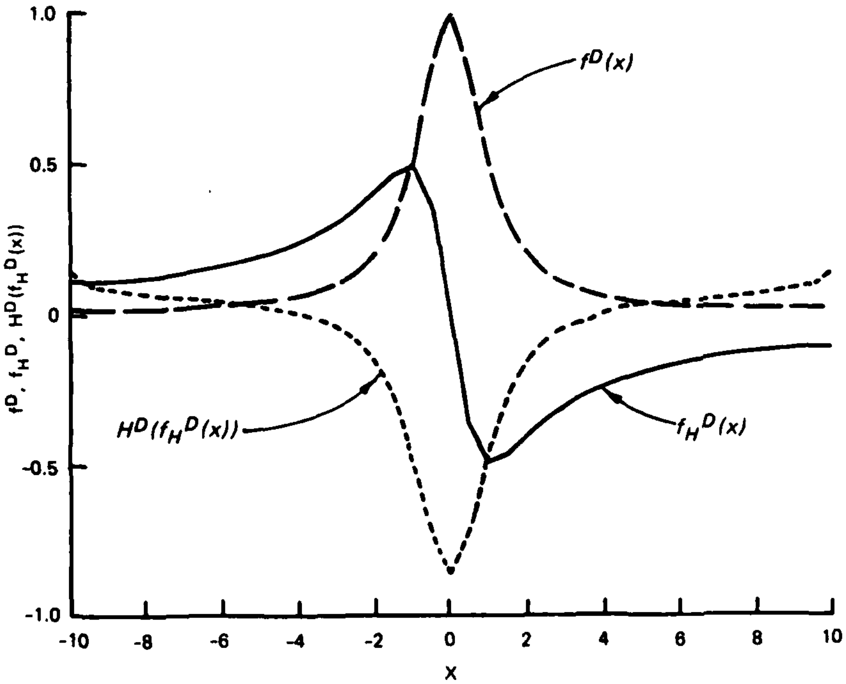


Figure 37. HILBERT test case for $\Delta x = 0.5$ and $-10 \leq x \leq 10$

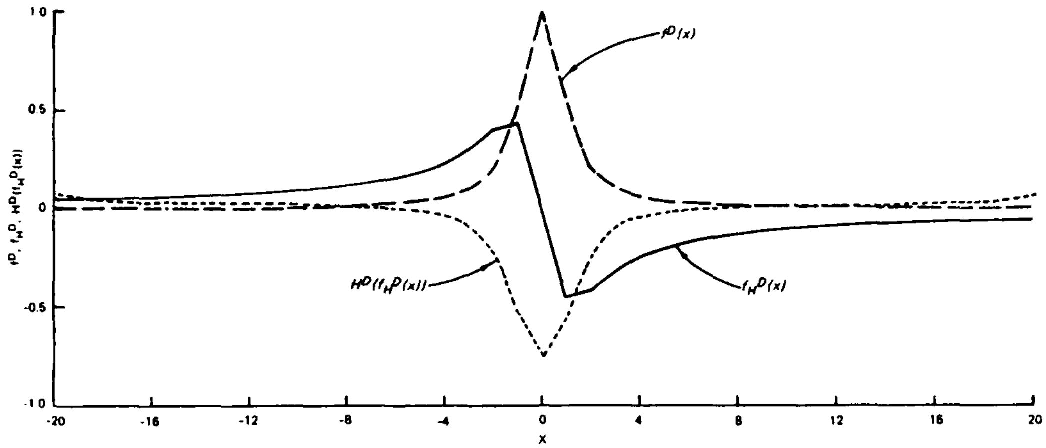


Figure 38. HILBERT test case for $\Delta x = 1$ and $20 \leq x \leq 20$

Test Case				
Δx	Profile Length	$\lvert H^D(f_H^D(x)) \rvert_{max}$	Half-Width at Half-Maximum	Value at Ends of Profile
1	-5, 5	0.66	2.60	0.17
0.5	-5, 5	0.80	2.00	0.22
0.25	-5, 5	0.86	1.86	0.27
1	-10, 10	0.71	1.50	0.12
0.5	-10, 10	0.86	1.05	0.14
1	-20, 20	0.74	1.45	0.07
Analytic results		1.0	1.0	$\rightarrow 0$

75. The function $f(x)$ in Equation 12 is a stringent test for the discrete Hilbert transform algorithm, since it is so sharply peaked. Sampling at $\Delta x = 1$ is rather coarse for this particular $f(x)$, yet even for this case the results of the test (two successive applications of the discrete Hilbert transform) improve significantly as the profile length is increased. Also, for a given profile length such as (-5, 5), the test results improve significantly as Δx is decreased, although the usual "law of diminishing returns" holds. Of course, simultaneously decreasing Δx and increasing the profile length is the key to improving the results. The column listing the value at the ends of the profile indicates the "errant" behavior of the ends of the doubly transformed function due to the manner in which the profile is truncated. Increasing the profile length decreases the magnitude of this "errant" behavior, while decreasing Δx increases it.

Manatee Springs Microgravimetric and Gravity-Gradient Surveys

Scope of microgravimetric and gravity-gradient surveys

76. The microgravity survey at the Manatee Springs site consisted of 186 stations over a 100- by 400-ft (∿30- by 122-m) area with a basic grid interval of 20 ft (6.1 m). LaCoste and Romberg Model D-25 gravity meter was used for the survey. The survey grid was oriented approximately perpendicular to the known trend of the cavity system, as shown in Figure 3. Grid point (0,200) was used as a base station and was reoccupied on an average of once every 30 min (see Figure 19). Details of the microgravity survey procedure can be found in Butler, Whitten, and Smith (in press). In addition to the microgravity survey, a tower vertical gradient survey (Butler, 1980a) was conducted along the SW-NE line extending from (40,0) to (40,400); this survey consisted of 21 vertical gradient stations.

Residual gravity anomaly map

77. Results of the microgravity survey and the procedures used in determining the residual gravity anomaly values are discussed earlier in this Part and presented in Figures 22-25. The first-order residual anomaly map in Figure 24 is selected as the representation which reflects the gravity anomaly due to the main Manatee Springs cavity. The broad negative anomaly over the known cavity system in Figure 24 is consistent in magnitude and width with the known size and depth of the cavity system (see Figure 26). However, there are complexities or smaller anomalous features in the residual map which cannot be attributed to the main cavity; some of these smaller anomalies are due to smaller and shallower solution features or other density anomalies as discussed previously.

Vertical gradient survey results

78. The five tower measurement elevations shown in Figure 39 were utilized during the vertical gradient survey; because of difficulties in obtaining readings only five gravity values at the upper elevation h_4 were obtained along the profile line. Since the measurement sequence

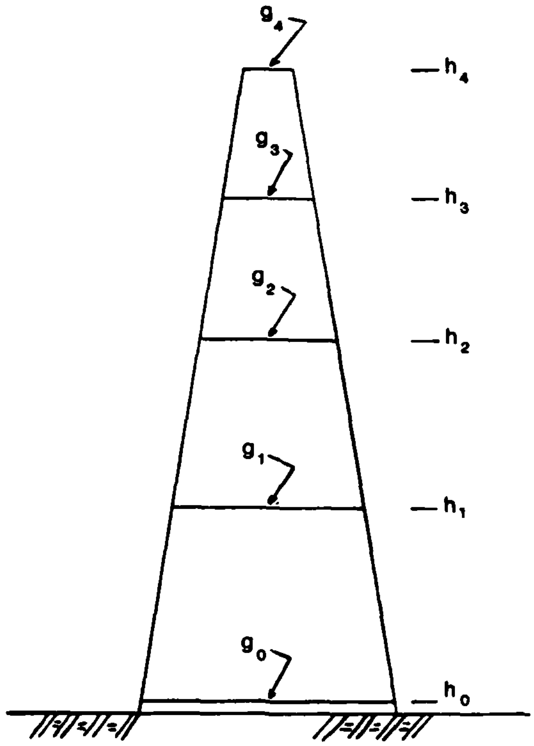


Figure 39. Illustration of the five gravity measurements and associated elevations which were utilized to determine interval vertical gradients along a selected profile line at the Manatee Springs site; nominally, $h_1 \simeq 0.6$ m, $h_2 \simeq 1.0$ m, $h_3 \simeq 1.4$ m, $h_4 \simeq 1.6$ m

at each profile location required 15 to 25 min, the ground station h_o was reoccupied at the end of each sequence and the data were shift-corrected in the usual manner.

79. Considering elevations h_o, h_1, h_2, and h_3, six interval gradients can be determined as well as differential gradients at any point within the interval h_o to h_3 using a parabolic fitting procedure. Results of three of the determinations of vertical gradients are shown in Figure 40: $\Delta g'_{01}/\Delta z_{01}$ and $\Delta g'_{03}/\Delta z_{03}$, where $\Delta g'_{01} = g_1 - g_o$, $\Delta z_{01} = h_1 - h_o$, and similarly for $\Delta g'_{03}$ and Δz_{03}; $(\partial g/\partial h)_o$, which is the differential gradient at h_o, determined from a parabolic fit to the data at h_o, h_1, and h_3 and evaluated at h_o. The five values of $\Delta g'_{04}/\Delta z_{04}$ are also shown. All three profiles exhibit

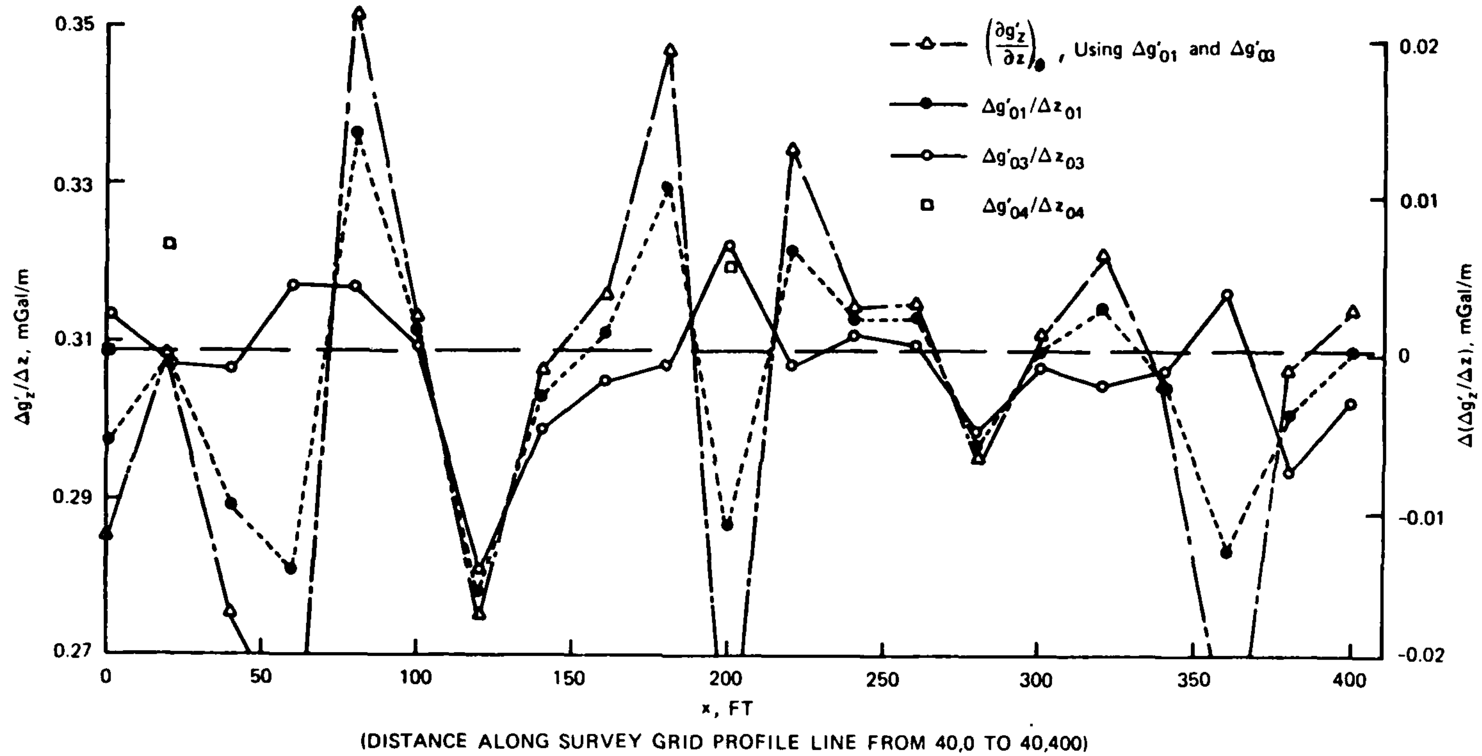


Figure 40. Interval vertical gradients along the (40,0) to (40,400) profile line at the Manatee Springs site

considerable variation, with several gradient anomalies as large as 10 percent of the normal vertical gradient. Generally, the $\Delta g'_{03}/\Delta z_{03}$ profile is smoother than the other profiles as expected, since it should be less affected by very shallow density anomalies. All three profiles behave qualitatively the same except at profile positions 0, 40 to 60, 200, and 360 where the $\Delta g'_{03}/\Delta z_{03}$ profile behavior is clearly at variance with the other two profiles. In many locations the three values are nearly identical; and at the 100- and 300-ft profile positions all four values are nearly equal and also nearly equal to the normal gravity gradient; which implies a linear variation of gravity with elevation at these locations. There is, however, no obvious indication of an anomaly which could be caused by the subsurface cavity system.

Horizontal gradient determinations

80. Using the gravity data along the selected profile line, interval horizontal gradient profiles can be determined using various values of Δx . Clearly, for cases where there is no regional gradient along the profile line, or where the regional gradient is linear in the profile direction, the results will be identical whether the Bouguer anomaly or the residual anomaly values are used to compute horizontal gradient. When the above conditions do not hold, there will be a regional component present in the gradient profile. In the present case, it is preferable to use residual gravity values. Horizontal gradient profiles for Δx equal to 20, 40, and 80 ft (6.1, 12.2, and 24.4 m) are shown in Figure 41, where the residual gravity values from Figure 23 were used. The profiles in Figure 41 clearly become smoother with increasing Δx . Importantly, all three profiles show "average behavior" consistent with the known cavity system with center at profile position 200 ft. The Δx = 20-ft profile, however, is so erratic that the "cavity gradient signature" is effectively masked. The gradient "signature" of the cavity is enhanced by Δx values which are larger than the effective depths of the shallow anomalous features causing the erratic behavior of the Δx = 20-ft profile. Accordingly, the Δx = 80-ft profile data will be used for the considerations which follow.

Comparison of results with two-dimensional model calculations

81. The cavity system was modeled as a two-dimensional, horizontal cylinder with rectangular cross section as shown in Figure 26, and TALGRAD was used to compute horizontal and vertical gravity gradients. In Figure 42, the computed horizontal gradient profile is compared with the measured horizontal gradient profile for $\Delta x = 80$ ft. The average behavior of the measured profile approximates the calculated profile quite well in amplitude and spatial wavelength, with the amplitude of the measured profile slightly larger on the right-hand side. HILBERT was used to compute a vertical gradient profile from the measured horizontal gradient profile for $\Delta x = 80$ ft . This profile, computed by the Hilbert transform procedure, is compared in Figure 43 to the vertical gradient profile computed from the two-dimensional model. Again, the agreement between the two profiles in Figure 43 is good with respect to amplitude and spatial wavelength; however, the Hilbert transform profile has maximum amplitude at position 240 ft rather than 200 ft and has a prominent positive peak at 320 ft.

82. Gradient space plots prepared from the profiles in Figures 42 and 43 are shown in Figure 44 for the two-dimensional model and for data derived from the field measurements. The somewhat subtle differences noted in the profile data plots are more apparent in the gradient space plot; to profile position 200 ft (lower half of plots in Figure 44), the agreement between the two plots is good, but from profile positions 200 to 400 ft (upper half of plots in Figure 44), the two plots differ significantly in magnitude. The results in Figure 44 suggest that the simple two-dimensional model which was selected may not approximate the cavity system very well. Indeed, reports of both a cave diving team and a very limited verification drilling effort confirm that the cavity system is extremely complex. The cavity varies erratically in cross-sectional shape and size; a vaulted ceiling is common and numerous smaller branching cavities are present. Also, drilling indicates more extensive solutioning to the northeast of the (0,200) to (100,200) line than southwest of it, which is consistent with both the residual gravity map and the gravity-gradient results.

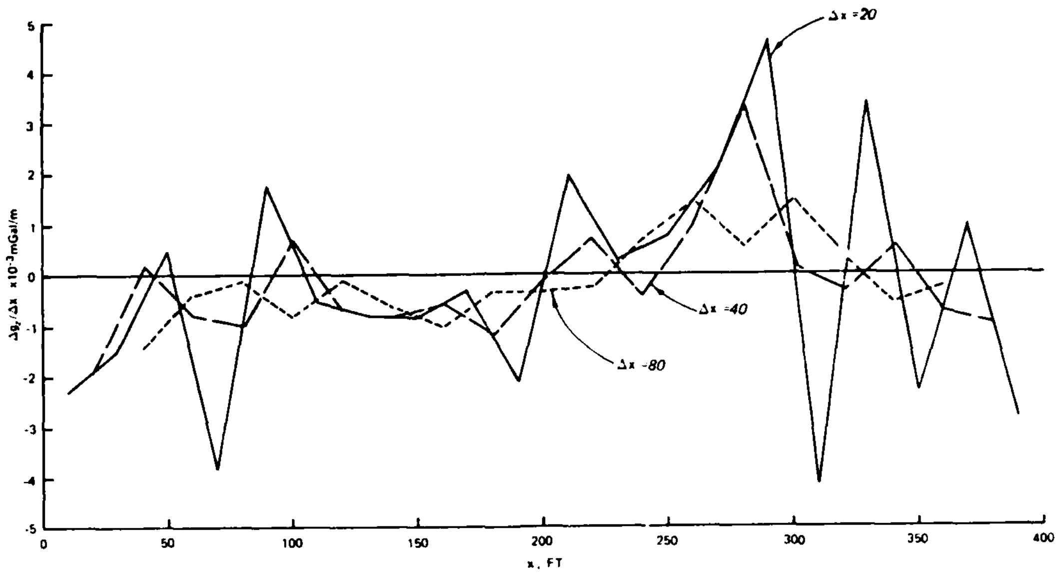


Figure 41. Interval horizontal gradient profiles for three values of Δx along the (40,0) to (40,400) profile line at the Manatee Springs site

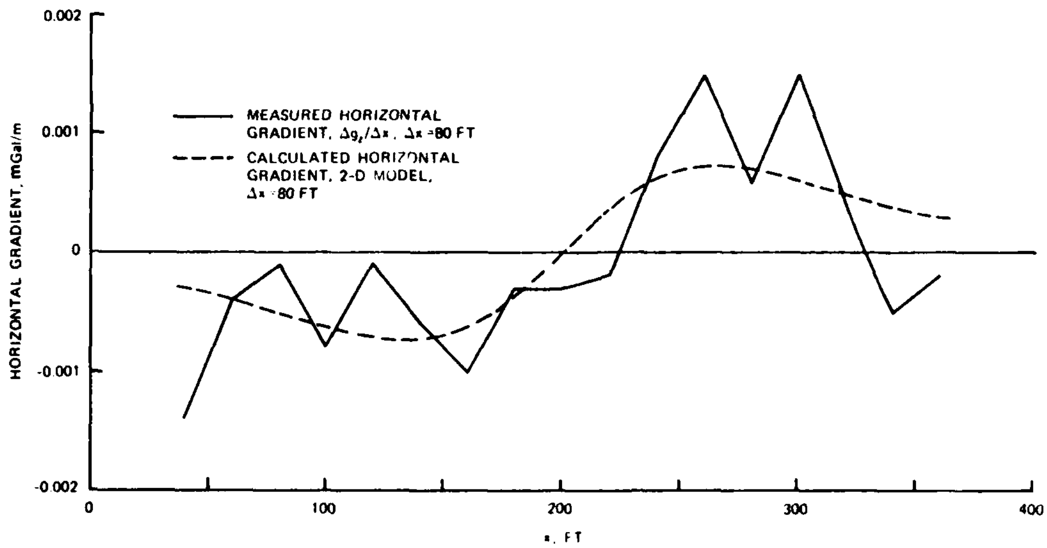


Figure 42. Comparison of measured and calculated (using TALGRAD) interval horizontal gradients along the (40,0) to (40,400) profile line at the Manatee Springs site

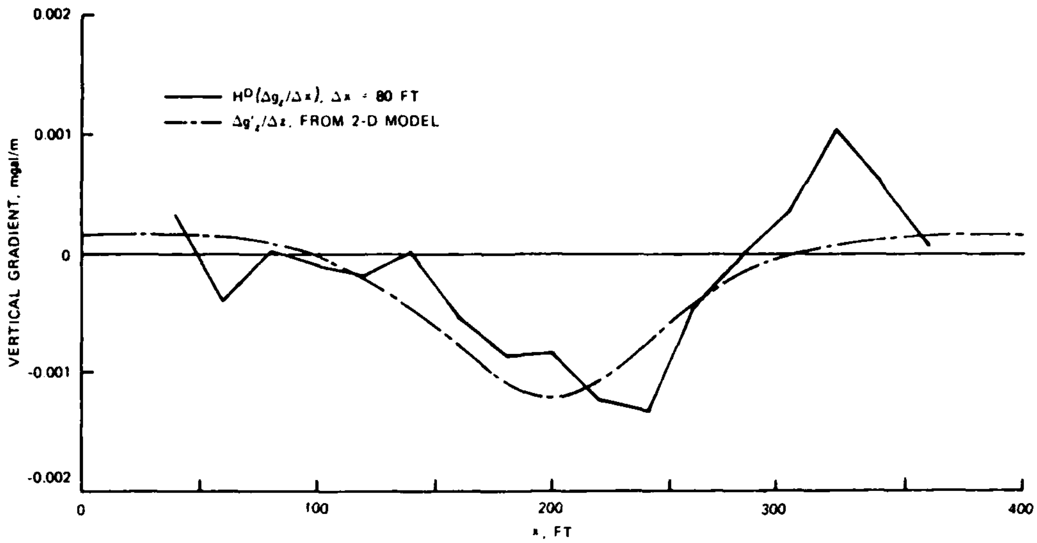


Figure 43. Comparison of vertical gradient profiles, determined from two-dimensional model calculations using TALGRAD and from the Hilbert transform of the measured horizontal gradient profile using HILBERT for the (40,0) to (40,400) profile line at the Manatee Springs site

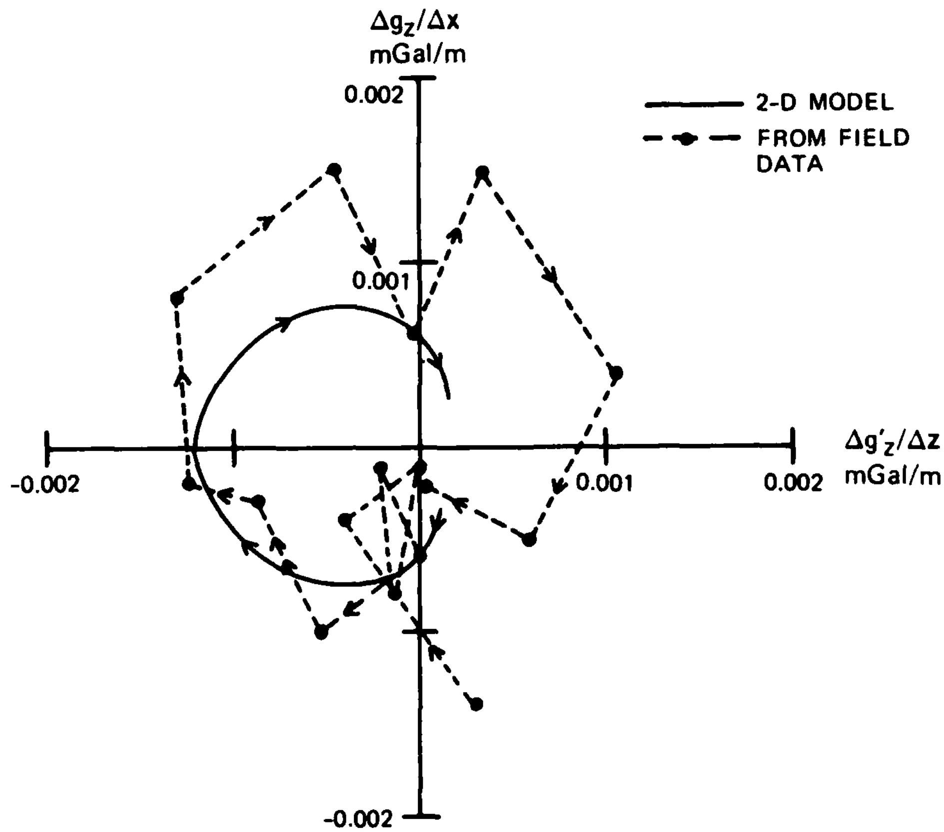


Figure 44. Gradient space plots for gradient data along the (40,0) to (40,400) profile line at the Manatee Springs site

Verification drilling results

83. Because of time and fiscal constraints, only a very limited number of verification borings was possible at the Manatee Springs site. Unfortunately, the six verification borings were located to investigate various gravity anomalies as well as anomalies indicated by other geophysical surveys and not specifically to investigate anomalies along the gravity-gradient profile line. Likewise, most of the six borings placed to accommodate crosshole surveys of various types were placed to the northeast of the gradient profile line. Two borings, however, allow direct confirmation of vertical gradient anomalies shown in Figure 40. Overall the borings indicate that typically limestone is encountered at depths of 13 to 17 ft (4 to 5.2 m), although limestone pinnacles rise to within 5 ft (1.5 m) of the surface in placed and clay-filled pockets in the top of the limestone extend to depths of 27 ft (8.2 m) in places. A boring near gradient profile position 120 ft encountered a clay pocket which extended to 27-ft depth (limestone typically is encountered at 17-ft depth in this area); the vertical gradient profiles show a prominent negative anomaly at this location. Another boring near gradient profile position 280 ft encountered a clay pocket extending to 16-ft depth (limestone typically is encountered at 13-ft depth in this area); the vertical gradient profiles show a negative anomaly at this location.

84. The boring near gradient profile position 280 ft encountered a significant clay-filled cavity in the 90- to 105-ft (27- to 32-m) depth range; this is the same depth range as the known water-filled cavity to the southwest. The discovery of this clay-filled cavity feature suggests that solution features extend considerably northeast of the known cavity system under the gradient profile line, which is completely consistent with the gradient profile data in Figures 42-44.

Conclusions

85. The results of drilling at the Manatee Springs site confirm that the larger magnitude, short spatial wavelength anomalies which appear in the measured vertical gradient profiles in Figure 40 are due primarily to relatively shallow (<20 ft or 6 m) density anomalies such as clay pockets and limestone pinnacles. The lower amplitude, longer

spatial wavelength anomalies which appear in the measured horizontal gradient and Hilbert transform vertical gradient profiles in Figures 42 and 43 are due to the deeper (>80 ft or 24 m) main cavity system. The large amplitudes of the vertical gradients caused by shallow feature at the Manatee Springs site completely mask any possible expression in the measured vertical gradient profile of the low amplitude anomaly due to the deeper cavity system, at least in vertical gradient profiles determined with a short, portable tripod. A much taller tower (>20 ft or 6 m in height) with lower measurement station several feet (1 to 2 m) above the ground would be required to have any chance of detecting the vertical gradient anomaly caused by the cavity system; even then, it is unlikely that a 0.001 mGal/m gradient anomaly could ever be detected by a tower (interval) measurement procedure.

Gravity-Gradient Analysis of a Selected Gravity Profile Across Dry Lake Valley, Nev.

Concepts

86. One of the important and powerful aspects of the gravity-gradient analysis and interpretation procedures (Butler, 1980a, b, c) is that they can be applied to existing good quality gravity data at any scale. Gravity profiles can be digitized; and using the basic digitizing interval as a starting point, horizontal gradient profiles can be computed for various multiples of the basic interval. The Hilbert transform procedure is used to compute vertical gradient profiles, and then the gradient space plot and modulus of the analytic signal plot can be constructed. Implicit in the procedure just described is that the structural aspects of the problem being analyzed are two-dimensional. If a gravity contour map is used as a starting point, gravity profiles should be selected across and approximately perpendicular to the trend of anomalies which in some sense can be considered to be caused by a two-dimensional structure. If the starting point is a gravity profile, it should cross a known structure which can be considered approximately two-dimensional in nature, striking nearly perpendicular to the profile

line. An example of the first of these cases is presented here, i.e., a gravity profile is selected perpendicular to the major trend of an elongated gravity anomaly associated with an alluvial basin in the Basin and Range Province.

Background

87. The Dry Lake Valley gravity survey is briefly discussed earlier in this Part as an example of the use of TALGRAD.

88. Dry Lake Valley is located in central Lincoln County, Nev., approximately 170 km north-northeast of Las Vegas. The gravity survey, consisting of 1069 stations in and around Dry Lake Valley, was conducted by the Defense Mapping Agency (DMA) in the summer of 1977. Correction of the gravity data was performed by DMA and Fugro National, Inc. personnel to produce a Bouguer anomaly map. The regional field was derived by fitting a second-order polynomial surface to Bouguer anomaly values on bedrock outcrop stations around the valley. Subtracting the derived regional field from the Bouguer anomaly map yielded the residual anomaly map shown in Figure 28. Complete details of the site, gravity survey, and data correction procedures are given in Fugro National, Inc. (1980) and McLamore and Walen (1979).

89. Dry Lake Valley exhibits typical basin and range structure, with the valley probably occurring above a graben between two high angle normal basement faults on the east and west sides of the valley. Outcrops in the mountains on the western side of the valley are predominantly Tertiary ash flow tuffs with some Paleozoic carbonates; while the mountains on the eastern side are predominantly the Paleozoic carbonates with only minor amounts of the Tertiary tuffs. The valley fill consists of unconsolidated to partially consolidated silt, sand, and gravel derived from adjacent highlands. Primarily the fill materials are Tertiary and early Quaternary alluvial fan deposits (72 percent by area) and fluvial and stream terrace deposits (16 percent).

90. The three-dimensional model and interpretation discussed previously and shown in Figure 29 were constrained by (a) results of two long intersecting refraction lines in the north end of the valley, (b) several shallow (<500 ft or 150 m) boreholes throughout the central

portion of the valley, and (c) a knowledge of the structural style of the region. A density contrast of -0.45 g/cm^3 (between alluvium and carbonate bedrock) was determined by trial and error gravity interpretation to yield the best "tie" of the refraction results. This density contrast agrees with published density values for bedrock and alluvium materials in the area (McLamore and Walen, 1979). An interesting feature of the interpretation shown in Figure 29 is that the placement of the faults was determined from an examination of the second vertical derivative of the gravity field; i.e., the faults are placed along the zero contour of the second derivative field. This procedure places the surface trace of the eastern boundary fault about 1 mile west of the surface cracks in the alluvium, which have been mapped as a fault.

<u>Gradient interpretation</u>

91. Profile AA′ in Figure 29 was chosen for gradient analysis and is plotted in Figure 45.* The gravity profile was digitized at 1-km intervals and horizontal gravity gradients were calculated for $\Delta x = 1$,

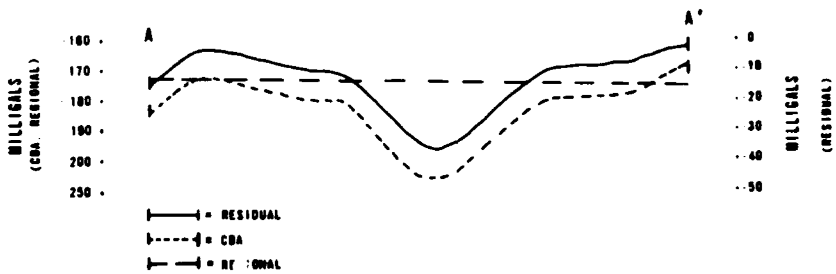


Figure 45. Bouguer anomaly (CBA), regional field, and residual anomaly for Profile AA′ (see Figure 28)

2, 3, and 5 km. HILBERT was used to calculate vertical gradients from each of the horizontal gradient profiles, and the gradient profiles for the four cases are shown in Figure 46. The gradient profiles clearly become smoother and exhibit fewer "complexities" as Δx increases due to the filtering properties of the interval measurement procedure; and the gradient profiles for $\Delta x = 5$ m closely resemble those for a

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* A much larger version of this gravity profile was used for digitization.

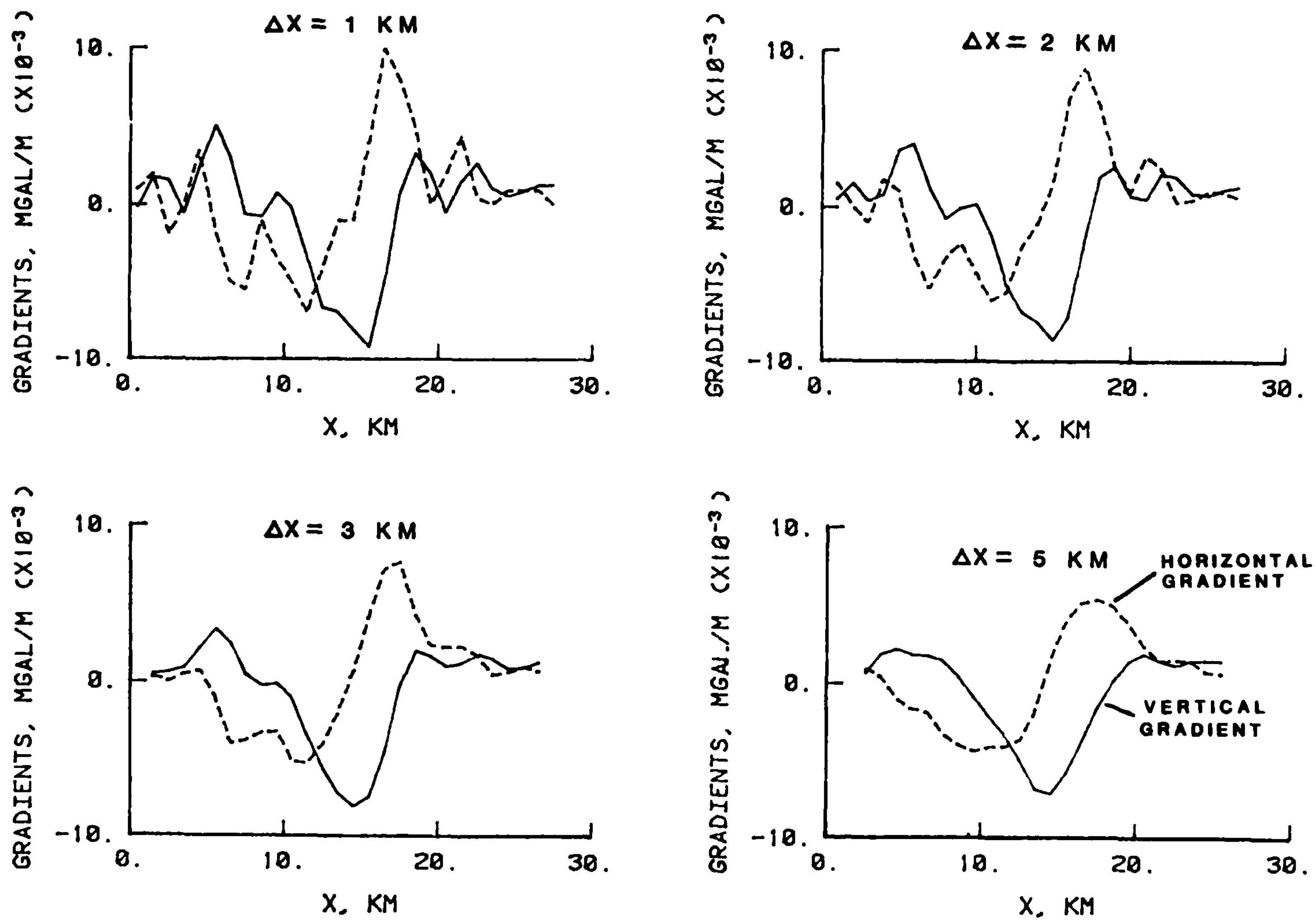


Figure 46. Measured horizontal gradient profiles for four values of Δx and associated computed vertical gradient profiles along AA′ (see Figure 28)

horizontal cylinder (the simplest two-dimensional structure). The gradient profiles for $\Delta x = 1$ km , however, exhibit features, in the central portion, which closely resemble the profiles for a grabenlike structure. Gradient-space plots for the $\Delta x = 1$ and 5 km cases are given in Figure 47, which further illustrates the qualitative features discussed above (Butler, 1980 a, b, c).

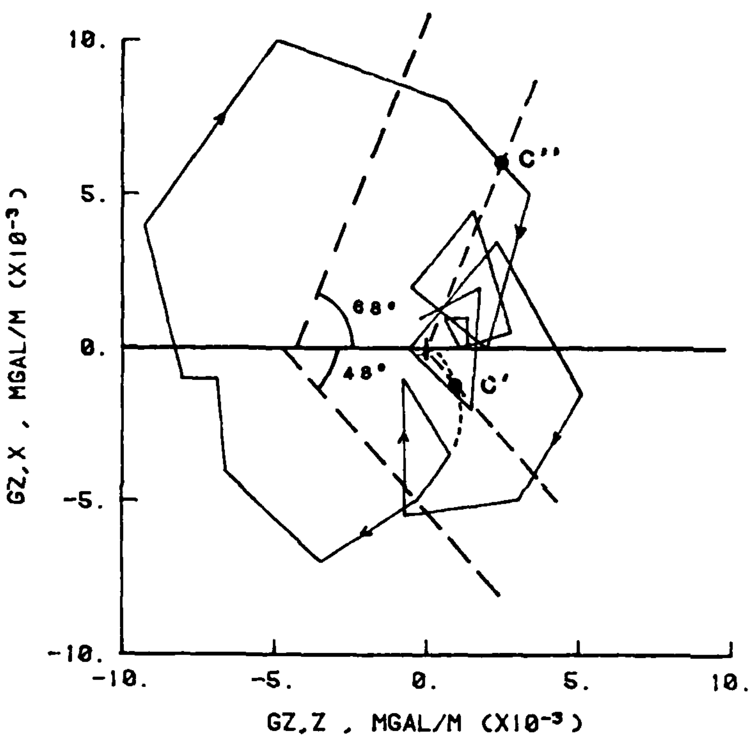
92. For purposes of gradient interpretation, the gradient profiles and gradient-space plot for $\Delta x = 1$ km will be utilized.* Figure 48 is a larger scale plot of the gradient profiles for $\Delta x = 1$ km . It is evident from an examination of Figures 47a and 48 that the structure causing the gradient anomalies is more complex than a grabenlike structure with nearly equal side slopes and a horizontal "floor." Because of the complexities evident in the gradient-space plot, the interpretation procedure will rely on an alternative procedure in which (a) the vertical gradient profile is used to locate profile positions of structural corners, and (b) the gradient-space plot is used to determine slope angles of the graben bounding-faults and their projected surface intersection points.**

93. Six points are labeled in Figure 48, with points E, F, G, and H assumed to be associated with the central graben structure. Points D and I are located at profile positions corresponding exactly to locations of vertical gradient peaks, while points E, F, G, and H are shifted by $\Delta x/2$ relative to the associated vertical gradient peaks

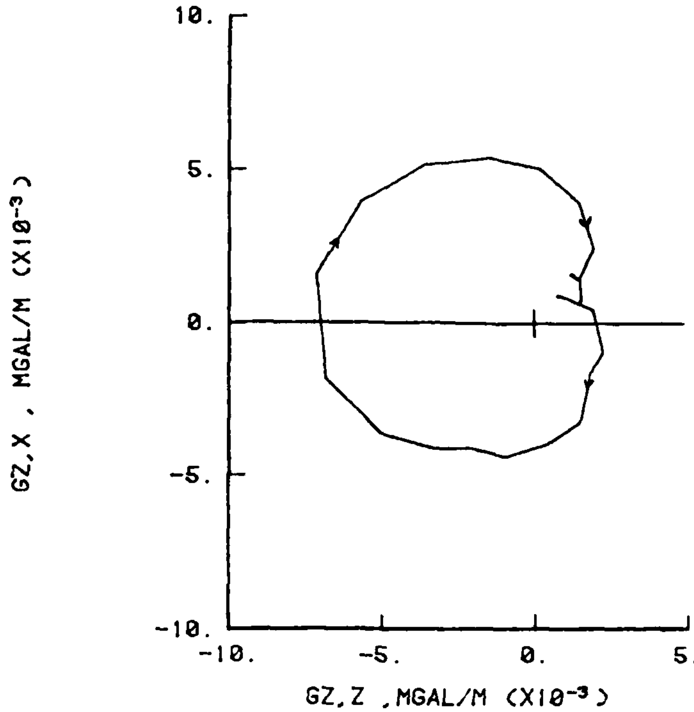
---

* The result of using the profiles for $\Delta x = 2$ km for the interpretation would be nearly identical to that presented for the $\Delta x = 1$ km case. The interpretation resulting from using the $\Delta x = 3$ or 5 km profiles would be different, since the gradient features due to shallow structures cannot be recognized.

** For the ideal case of a nearly symmetric, graben structure model, generally all of the parameters of the model can be obtained from an analysis of the gradient-space plot alone, including profile locations and depths of the four corners of the model. The gradient-space plot will be the superposition of two ellipses, and the inclination of the long axes of the ellipses to the horizontal axis (vertical gradient axis) defines directly the slope angles of the sides of the graben model relative to the horizontal.



a. Gradient-space plot for Δx = 1 km case



b. Gradient-space plot for Δx = 5 km case

Figure 47. Gradient-space plot for two of the cases shown in Figure 26

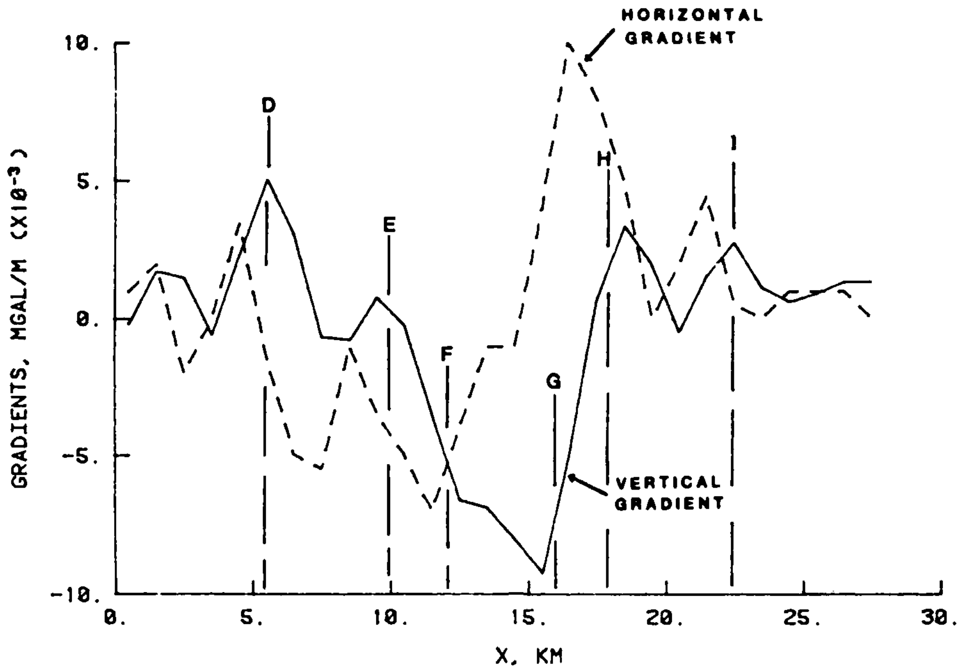
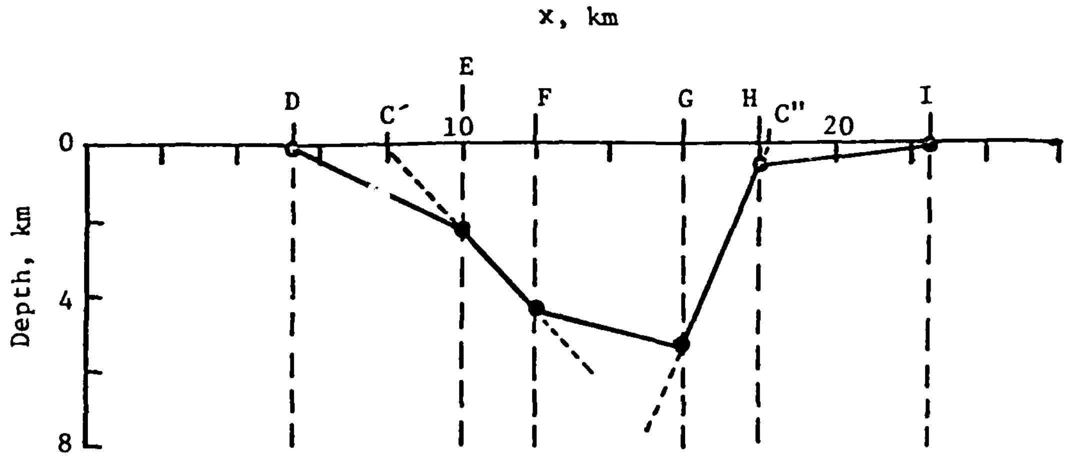


Figure 48. Gravity-gradient profiles along AA′ (see Figure 28) for Δx = 1 km

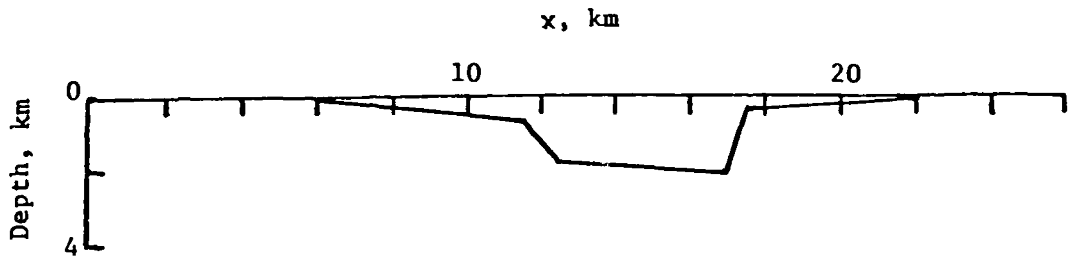
to qualitatively compensate for gradient profile "broadening" due to sampling and superposition effects.

94. Angles of -48° and 68°, relative to clockwise rotations from the $g_{z,z}$ axis, are defined in Figure 47a for the lower and upper ellipses, respectively. Also, points labeled C′ and CC′ and corresponding profile locations are shown for the lower and upper ellipses, respectively; these points are assumed to be the surface projection of the side faces of the graben structure. The slope angle and C′ for the upper ellipse are fairly well defined. However, the slope angle and C′ for the lower ellipse are not as well defined; there is clearly subjective judgment involved in the definition of C′ .

95. By use of the parameters defined in Figures 47a and 48, the structural geometry shown in Figure 49a can be constructed. Points D and I are assumed to be at or very near the surface and connected to points E and H, respectively. by straight lines. Maximum depth to rock of ∿5.4 km is predicted at point G. The structural model of the valley



a. Structural model deduced by gradient methods



b. Structure model from 3D gravity inversion

Figure 49. Structural models deduced from Dry Lake Valley gravity profile AA´ using two different interpretive methods

fill-bedrock geometry is deduced directly from the gradient data with no assumptions regarding density contrasts.

Comparison of gradient and three-dimensional gravity interpretation

96. The results of the three-dimensional gravity inversion along profile line AA´ are shown in Figure 49b (also in Figure 30). Qualitatively, the two interpretations shown in Figure 49 are very similar, and the slope angles of sides EF and GH in Figure 49a and their counterparts in Figure 49b differ by 1 and 5 deg, respectively. The primary quantitative difference is the rather dramatically larger predicted depth to the

carbonate bedrock predicted by the gradient model. Profile locations of points D and I are approximately the same in both models; however, profile locations of points E, F, G, and H in the two models differ by amounts varying from 0.5 to 1.5 km.

97. Although several explanations might be advanced to explain the discrepancies between the two models in Figure 49, only two will be presented and discussed: (a) possible errors in the locations of points E, F, G, and H in the gradient model, and (b) errors in depth in three-dimensional gravity model due to selection of density contrast. Small errors in location and hence spacing of the points E, F, G, and H could produce significant errors in depths to the corners of the structural model, due to the relatively steep slopes of the sides of the graben structure. If the model shown in Figure 49b, from the three-dimensional gravity inversion, is correct, then using the depths to the corners E and H as a measure of the parameter ζ_o, the "depth" to the model, results in $\Delta x/\zeta_o \sim 2$ ($\Delta x = 1$ km, $\zeta_o \sim 0.5$ km). From previous considerations (Butler, 1980a, b, c), it is known that amplitude attenuation and increase in spatial wavelength of the horizontal gradient profile become significant for $\Delta x/\zeta_o = 1$ and become very pronounced for $\Delta x/\zeta_o = 2$. These distortions of the horizontal gradient profile due to the sampling process will be reflected in the vertical gradient profile (computed with HILBERT) by increased separation and broadening of the peaks (relative maxima) corresponding to corners E and H, leading to values for the distances EF and GH which are too large. It is noteworthy, however, that the locations of corner H and its surface projection C" for the gradient model in Figure 49a are more consistent with surface cracks in the alluvium than the corresponding locations in Figure 49b.

98. An equally plausible explanation for the differences in the two models in Figure 49 is that the predicted depths in Figure 49b are too small due to the use of a density contrast which was too large (Butler, 1980a). The density contrast of -0.45 g/cm^3 used for the three-dimensional gravity inversion corresponds to the density contrast for shallow sediments relative to basement rocks. Since the sediment density

AD-A121 196 ANALYTICAL AND DATA PROCESSING TECHNIQUES FOR INTERPRETATION OF GEOPHYSIC..(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS GEOTE.. 2/3

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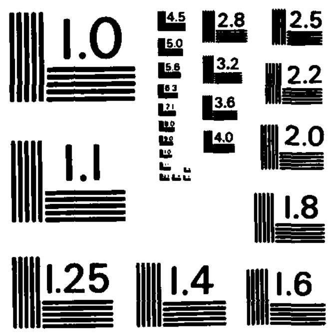

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

will increase with depth, $-0.45\ g/cm^3$ must be viewed as a maximum density contrast (Fugro National, Inc., 1980). Thus, the depths calculated from the three-dimensional inversion are likely too small, particularly for the base of the graben. Additional modeling with different density contrasts or a density contrast function that decreases with depth was not considered to be justified by Fugro because so little is known about the actual density distribution in and around the valley. Without further information, such as a deep boring in the center of the valley or a long refraction line in the center of the valley, it is not possible to resolve the discrepancy between the two models in Figure 49. Density contrast considerations seem clearly to favor a valley model with greater depth than in Figure 49b. Since the model in Figure 49a, deduced by gravity-gradient techniques, was produced without assumptions regarding density contrast, it seems to be the preferred model. The best constant density contrast for the valley, corresponding to the gradient model in Figure 49a, could not be determined by using TALGRAD in an iterative fashion, varying only the density contrast until the calculated and measured gravity profiles agree. This example is presented in considerable detail to illustrate the manner in which some of the analytic techniques developed in this research effort can be utilized to analyze field data to determine geologic structure and geophysical properties.

PART IV: SEISMIC METHODS

Background

99. The seismic methods all involve the generation, propagation, and detection of seismic waves. Seismic waves are generated in three ways in surveys for geotechnical applications: impact sources, e.g., weight drop or hammer blow; explosive sources, e.g., dynamite, exploding bridgewire (EBW) detonators, and air guns*; and vibratory sources (constant frequency or swept frequency sources). Detection of the seismic waves is generally by velocity transducers called geophones. The objective of the seismic methods is to deduce properties of the media through which the seismic waves pass from properties of the detected wave forms (primarily the arrival times of various events or types of waves at the geophones). Two seismic methods are considered here: the seismic refraction method and the crosshole seismic method.

Seismic refraction method

100. The seismic refraction method is a surface survey technique in which the source locations and geophones are along a common line. Figure 50 illustrates the concept of the seismic refraction method, where the time-distance plot represents the arrival times of the first event at each geophone location. The first event at a given geophone will be due to a wave which propagates directly from the source or to a wave which is refracted along an interface with a higher velocity material. The first-arrival time-distance plot can be analyzed to give the velocities of subsurface soil/rock layers and depths to interfaces; Figure 50 illustrates the analysis for the simple case of two horizontal layers (Department of the Army, 1979).

101. For the case of three horizontal layers, the analysis of the time-distance plot to yield layer velocities and interface depths is still tractable by manual methods. Also, the case of two layers where the interface dips relative to the surface can be similarly analyzed

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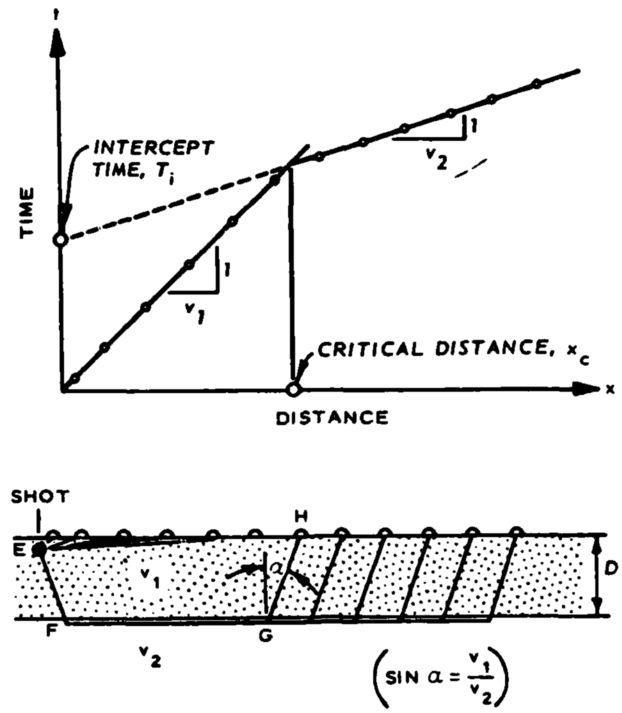
* Air guns generate seismic waves by a sudden release of compressed gas.



$$D_1 = \frac{x_c}{2}\sqrt{\frac{v_2 - v_1}{v_2 + v_1}}$$

Figure 50. Simple two-layer case with plane, parallel boundaries, and corresponding time-distance curve (after Redpath, 1973)

using manual methods (Department of the Army, 1979; and Telford et al., 1976). However, for the cases of greater than three horizontal layers and greater than two dipping layers, a programmable calculator or a minicomputer is desirable for the interpretation. The presence of dipping layers is indicated by an examination of the time-distance plots from forward and reverse "shooting" along a seismic survey line, i.e., from data obtained by using a source at each end of the geophone line. Figure 51 illustrates the appearance of the time-distance plot for a two-layer case with dipping interface, where the apparent velocity of the second layer is always greater when "shooting" in the updip direction.

102. In the past, seismic refraction data processing has involved manual "picking" of first-arrival events and scaling arrival times, often

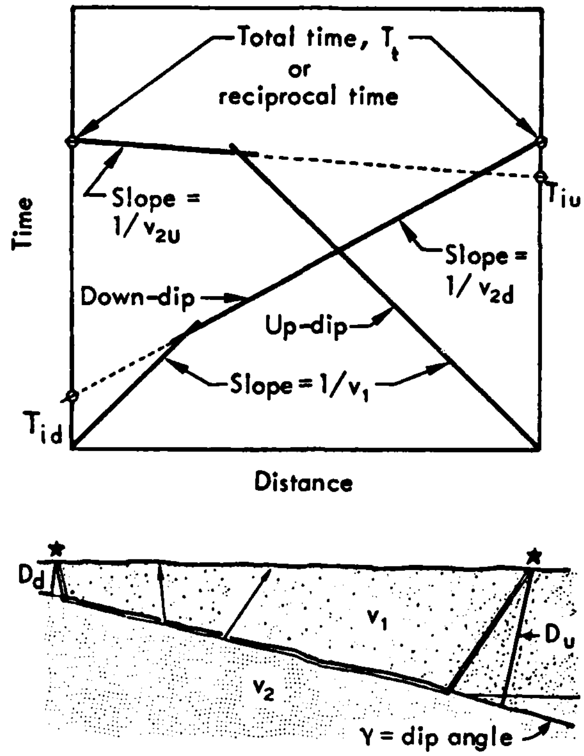


Figure 51. Example of dipping interface and concepts of "reverse shooting" and "apparent velocity" (after Redpath, 1973)

using a variable scale, from analog records. The time-distance data were then manually plotted, and straightline segments were fit to the data if possible. Velocities were then determined as the inverse of the slopes of the line segments. Interface depths and dips were then determined manually. This is still a common procedure, particularly when refraction survey data are processed and interpreted in the field.

103. Magnetic tape (analog) data recording has been used since the early 1950's and digital tape data recording since the early 1960's in seismic exploration for the oil industry. Associated with the digital seismic recording capability has been a rapid growth in digital data processing technology. This new technology makes possible the expeditious handling of enormous amounts of seismic data and reduces complex mathematical filtering operations to simple multiplications and additions of the digital data. Although many of the digital techniques which have been developed are applicable to any set of time series

data, the primary application has been to seismic reflection survey data. Also, equipment cost, physical size, and complexity of operation have prevented application of digital recording and processing technology to seismic refraction surveys for geotechnical applications. However, since the mid-1970's, small, relatively inexpensive digital seismic recording systems and powerful micro/minicomputers have been developed which can be utilized by groups involved in geotechnical applications of seismic methods.

104. This Part documents techniques developed to expedite seismic refraction data processing and to aid interpretation of seismic refraction results using minicomputers and time-sharing computer systems. While the data processing techniques which are described here must be considered an intermediate step in that analog field records are still utilized, the procedure has considerably reduced the manual effort involved in processing refraction survey data and helps prevent the data processing "bottleneck" which generally follows large field seismic investigations.

Crosshole seismic method

105. The crosshole seismic method utilizes seismic wave propagation between two or more boreholes to determine the seismic stratigraphy, i.e., the seismic velocities of subsurface materials and the locations of interfaces between materials with different velocities in site investigation programs. This method is used extensively in foundation investigations where both compression (P) and shear (S) wave velocities are required as input to dynamic analyses. Field procedures, equipment, and interpretation procedures for crosshole seismic testing are described in Department of the Army (1979), Butler and Curro (1981), and Butler, Skoglund, and Landers (1978).

106. Figure 52 (Butler and Curro, 1981) illustrates the geometry and concept of a crosshole seismic test. A seismic source and receiver are shown at the same depth in a pair of boreholes. The seismic source can be selected to preferentially generate vertically (horizontally) polarized S-wave energy if desired, and vertical-axis (horizontal-axis) receivers (perhaps in a triaxial geophone array) may be used to enhance

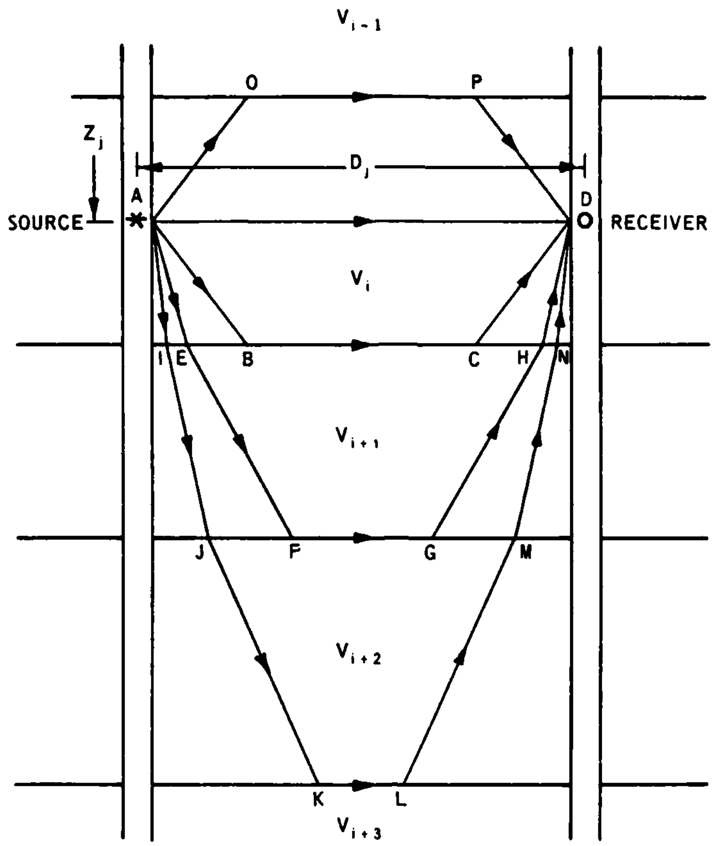


Figure 52. Crosshole seismic test geometry and possible propagation paths

S-wave detection. Explosive sources are rich in P-wave energy, and triaxial geophone arrays or even hydrophones (in fluid-filled boreholes) can be used as receivers for P-wave detection. Figure 52 indicates several layers with different seismic velocities (V_i) and thicknesses; the problem in crosshole seismic interpretation is to deduce this seismic stratigraphy from a data set which includes source/receiver depths and arrival times of events. Generally only the first-arrival times of P- or S-events are considered. The first P- or S-arrival at a given depth Z may be due to any one of the possible paths shown in Figure 52. The first-arrival event will be determined by the borehole separation D, and the magnitudes of the velocities. Dividing D by

the first-arrival time gives an apparent velocity which may not be equal to any of the layer velocities.

107. Butler and Cutto (1981) discuss some of the procedures and pitfalls involved in crosshole seismic interpretation, and Butler, Skoglund, and Landers (1978) present an algorithm and document a computer program (CROSSHOLE) for interpretation of crosshole seismic data. The program CROSSHOLE has been used extensively for the interpretation of crosshole seismic surveys. The program in its original form was somewhat cumbersome to use. Since it was written to be executed in a batch mode on a large computer, a data card deck had to be prepared and submitted for each set of crosshole data. This Part documents the conversion of CROSSHOLE to a time-sharing mode, making the program much more convenient to use and greatly decreasing the turnaround time.

Minicomputer Processing of Seismic Refraction Data

108. In this section, a processing procedure is described in which seismic refraction analog field records are processed by minicomputer. The procedure can be summarized as follows:

a. The analog records are examined in order to "pick" first-arrival events.

b. The analog records are placed on a large graphics tablet and the arrival times are digitized using a four-button graphics cursor.

c. The arrival time-distance data are listed in tabular form and are automatically stored in data files.

d. Arrival time-distance plots are automatically plotted if desired.

e. Straightline segments are manually fit to the data on the arrival time-distance plots.

f. Key points determined by intersections of the straightline segments are digitized using the graphics cursor.

g. Velocities (the inverse slopes of the line segments) and depths to interfaces are automatically calculated.

h. The procedure in steps a-d can be applied to any events which can be identified on the analog records.

BASIC-language programs for accomplishing the above processing steps have been written and are operational on a Tektronix Model 4051 minicomputer and associated digital plotter and graphics tablet; the procedure could easily by adapted for use with other minicomputers with BASIC-language capability. Input instructions for the processing programs follow and listings are given in Appendix H. It is important to note that the key steps in the operation (selecting of first arrivals (step a) and fitting line segments to the data (step e)) are still performed manually. Algorithms have not been developed to replace the judgment involved in these steps.

SEISDIG

109. SEISDIG is a general purpose seismic record digitization program. The program is well documented and prompting messages are printed before each input. The following items summarize the input/output sequence:

a. The first input request is for data identification, up to 72 characters in length.

b. The next four input requests are for (1) "shothole" coordinate, (2) distance from "shothole" to nearest geophone, (3) "shothole" depth (zero if source applied at surface, such as hammer blow), and (4) spacing between geophones along survey line.

c. Three input requests define the time scale: (1) digitize timing line just before time break, (2) digitize timing line 200 msec later (can be changed), and (3) digitize time break (times (1) and (3) can be the same).

d. Now the first arrivals are digitized using the four-button cursor as follows:

   (1) Press button "z" to digitize point.

   (2) Press button "1" to skip a trace.

   (3) Press button "2" to redigitize last point.

   (4) Press button "3" to digitize the last point of a record.

   (5) A tabular listing of arrival time-distance is produced.

   (6) An opportunity is now given to redigitize any of the points.

(7) The data are now stored in a data file on tape.

SEISPLOT

110. SEISPLOT reads the SEISDIG data files and produces time-distance plots. The program is well documented and prompting messages appear before each input. The following items describe the input/output sequence:

a. For each operation in the program, the following "menu" is printed, and selection of an item number executes the indicated operation:

(1) Enter data.

(2) Change or add data.

(3) Plot data and label axes.

(4) Choose between paper or CRT plot.

(5) Display data.

(6) Select symbol.

(7) Store data on tape.

(8) Read data from tape.

(9) Stop program.

b. If menu item (8) is selected, the number of the input data file is requested.

c. When menu item (3) is selected, x and y scale factors and axis labels are requested, and a plot is produced with x and y axes of 7 in. and 5 in. length, respectively.

REFINT

111. REFINT computes apparent velocities of line segments on the arrival time-distance plot from graphics cursor input of the intersection points of the line segments. Also, assuming the apparent velocities are true layer velocities, interface depths are calculated. If both forward and reverse time-distance plots are analyzed, true layer velocities are calculated using the harmonic mean formula.* The following items summarize the input/output sequence:

---

* i.e., $\frac{1}{V_T} = \frac{1}{2}\left(\frac{1}{V_F} + \frac{1}{V_R}\right)$; where V_T refers to true velocity, and V_F and V_R are the forward and reverse velocities, respectively; $V_T = V_F = V_R$ if the refractor is horizontal.

a. The first two input requests establish whether or not both forward and reverse data are to be processed, and, if so, which is to be input first.

b. The next three inputs are with the graphics cursor and establish the scale factors: origin, rightmost point on horizontal axis, uppermost point on vertical axis.

c. Next, the number of velocity layers associated with the forward and reverse data is input.

d. The crossover (critical) distances or line intersection points plus an additional point on the highest velocity line are now input with the cursor.

e. Next, a series of inputs establishes the geometry of the line, including source locations relative to the origin and source depths.

f. The tabulated output includes the critical distances, apparent velocities, and calculated depths (assuming horizontal refractors) for forward and reverse survey lines and finally the true velocities.

Example 1

112. Figure 53 is an example of the plotted output of SEISPLOT. The data are from a single-ended seismic refraction line. Triangles in Figure 53 represent first-arrival events at the 24 geophones of the line, and the source* point is at the origin. The survey consisted of a series of these single-ended refraction lines along a survey line parallel to a critical structure, with the source point advanced 50 ft each time. The hexagons in Figure 53 are the critical distances or intersection points at A and B and the additional point C on the highest velocity segment which are digitized as input to REFINT. Figure 54 is the tabular output from REFINT.

Example 2

113. Figures 55 and 56 illustrate an example similar to the one above. The objective of this survey was to evaluate a borehole air-gun as a source for seismic refraction surveys. The refracting interface in this case is the water table, and the depth to the interface of 11 ft calculated by REFINT (Figure 56) agrees with the known depth to the water table at the site.

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* The source for this survey was a vertically mounted "shotgun" which fires a slug into the ground.

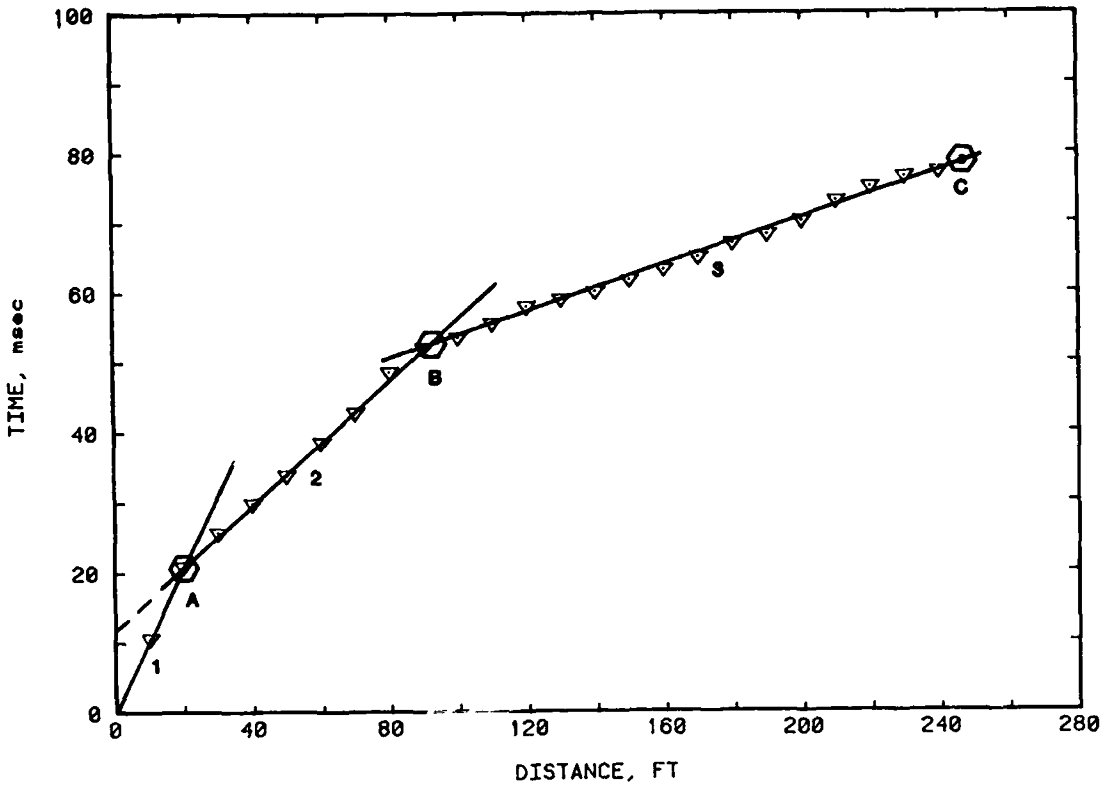

Figure 53. SEISPLOT output for single-ended seismic refraction line

FORWARD	REVERSE
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THE CRITICAL DISTANCES ARE:

X(1) = 20	X(1) = 0
X(2) = 93	X(2) = 0

THE APPARENT VELOCITIES ARE:

V(1) = 948 fps	V(1) = 0 fps
V(2) = 2295 fps	V(2) = 0 fps
V(3) = 6091 fps	V(3) = 0 fps

THE CALCULATED DEPTHS ARE:

D(1) = 6.48 ft	D(1) = 0.00 ft
D(2) = 36.55 ft	D(2) = 0.00 ft

THE TRUE VELOCITIES WERE NOT COMPUTED FOR THIS CASE

Figure 54. REFINT output for the time-distance plot in Figure 53

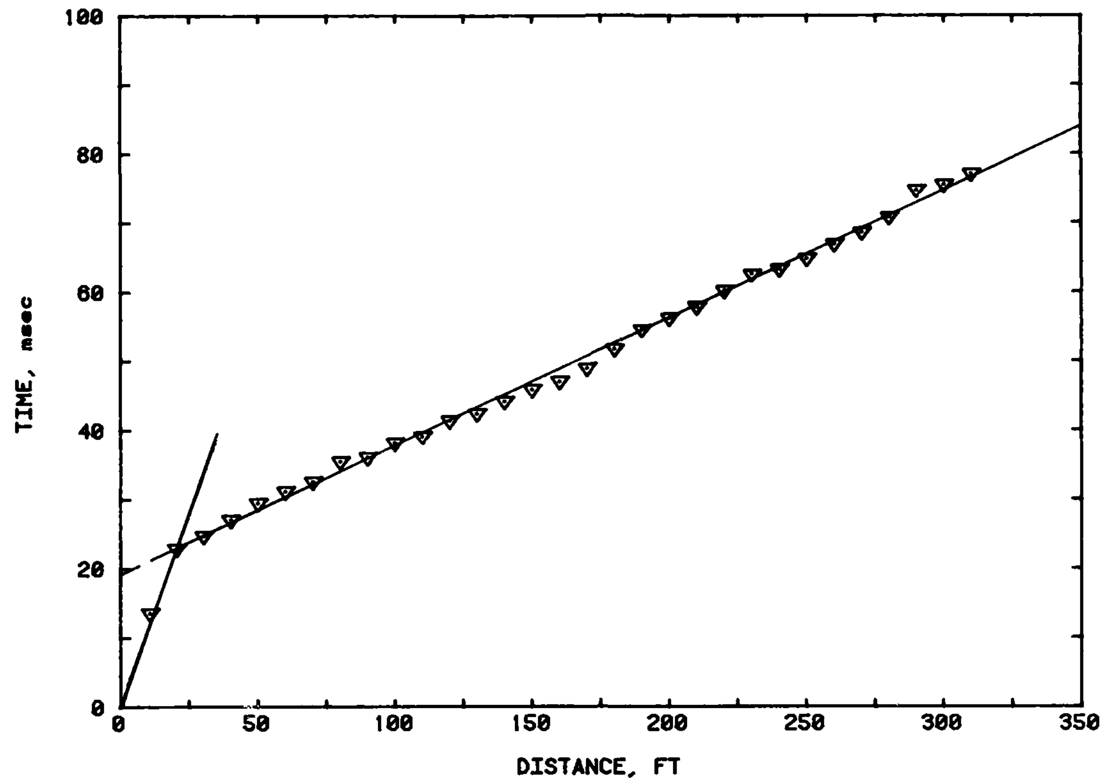

Figure 55. SEISPLOT output for refraction survey at a WES test site for evaluation of a borehole air-gun source

AIRGUN ON THE WES TEST SITE @ 1000 PSI

FORWARD	REVERSE

THE CRITICAL DISTANCES ARE:

X(1) = 21	X(1) = 0

THE APPARENT VELOCITIES ARE:

V(1) = 909 fps	V(1) = 0 fps
V(2) = 5397 fps	V(2) = 0 fps

THE CALCULATED DEPTHS ARE:

D(1) = 10.98 ft	D(1) = 0.00 ft

THE TRUE VELOCITIES WERE NOT COMPUTED FOR THIS CASE

Figure 56. REFINT output for case shown in Figure 55

Example 3

114. SEISDIG and SEISPLOT can be used to process any event which can be "picked" on the analog seismic records. Figure 57 illustrates the use of these two programs to process several events which can be identified on the analog records. Although a discussion of the events and their analysis is beyond the scope of this report, the events include direct waves (one of which is the air wave), first-arrival refracted compression wave, secondary refracted wave, the dispersed Rayleigh wave train, etc.

DOMER

115. A fourth BASIC-language program, DOMER, has been developed for processing events identifiable in the Rayleigh wave train on seismic refraction records. The processing sequence described here is not a rigorous Rayleigh wave dispersion analysis. In a rigorous analysis, the phase velocities (V_P) are determined as $V_P(T) = \Delta x/\Delta t$, where Δx is the separation of two geophones and Δt is the phase shift between the Fourier component with period T at the two geophones (determined by a Fourier analysis of the records from the two geophones). Group velocities (V_G) can then be calculated from the phase velocities using the dispersion relation: $V_G(T) = V_P(T) + T[dV_P(T)/dT]$. Plotting group and/or phase velocities as a function of period T or frequency $f(f = \frac{1}{T})$ yields the Rayleigh wave dispersion curves. Interpretation of a dispersion curve involves deducing a layered earth model with a theoretical dispersion curve that best matches the measured curve either with an iterative computer program or a set of standard dispersion curves (Grant and West, 1965); Dobrin, Simon, and Lawrence, 1951; and Ewing, Jardetzky, and Press, 1957).

116. The technique used here is to characterize an identifiable peak or trough in the Rayleigh wave train by its mean period, $\bar{T}$, which is determined simply as the time difference between the two neighboring troughs or peaks, respectively. If the distance x from the source to a given geophone is greater than the longest wavelength recorded by that geophone, then the group velocity for a period $T = \bar{T}$ is given by $C(T) = x/t$, with sufficient accuracy for most purposes, where t is

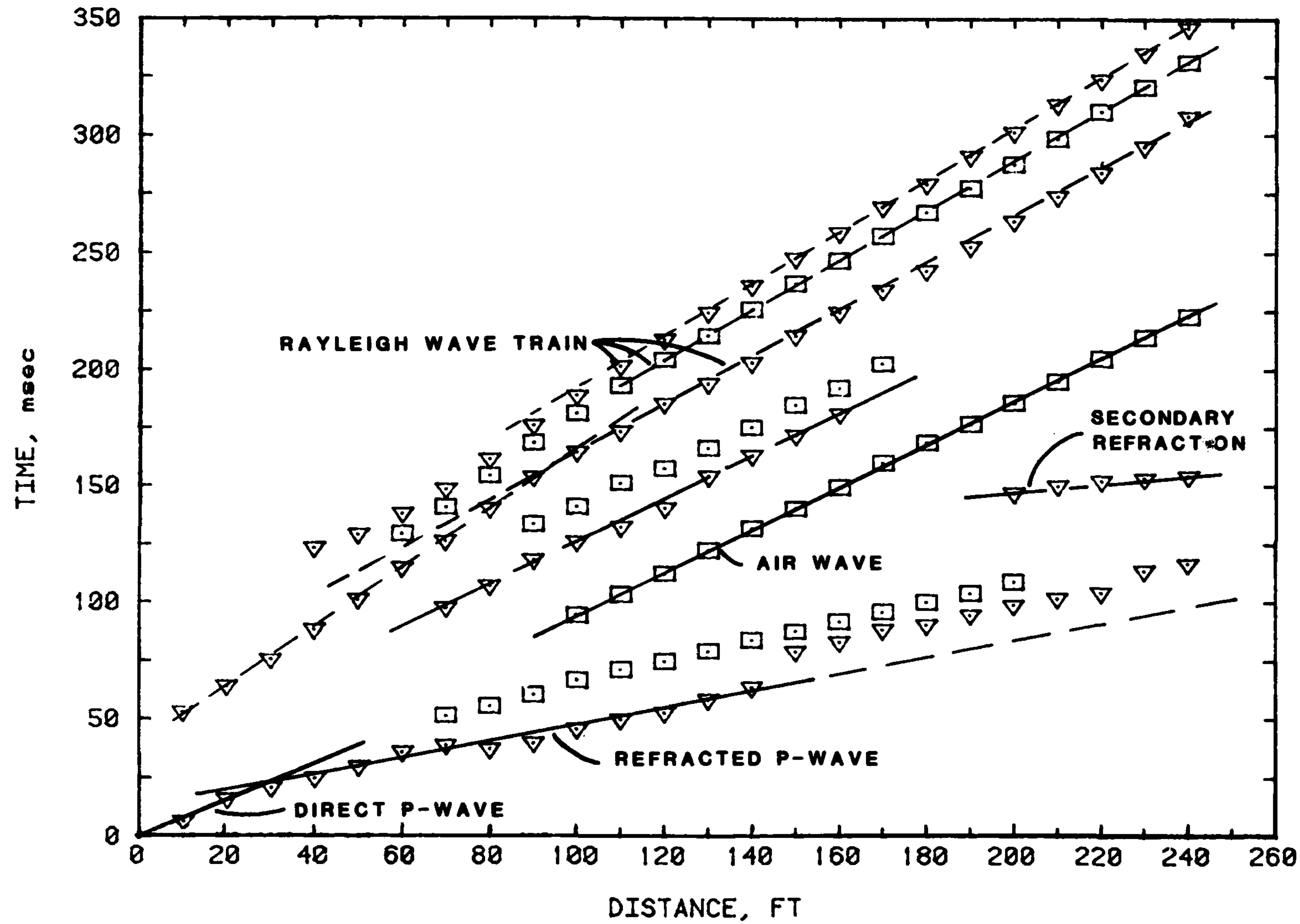

Figure 57. Example of the use of SEISDIG and SEISPLOT to produce time-distance plots for multiple events identifiable on a seismic refraction record

the arrival time for the peak or trough with mean period $\bar{T}$ at the geophone at distance x. For an event, peak or trough, in the Rayleigh wave train that can be followed or identified on two or more geophone traces, the phase velocity can be identified as the inverse slope of a line through the events in a time-distance plot (see Figure 57) _if_ the mean period of the event does not change significantly from one trace to the next (Grant and West, 1965). This technique, particularly the phase velocity determination, is seldom accurate enough for quantitative Rayleigh wave dispersion analysis. Also, it is often not possible to identify enough "events" to define the dispersion curves very well. However, the technique is useful for site characterization, such as location of areas with anomalously low Rayleigh wave velocity (hence, low shear wave velocity). The Rayleigh wave phase velocity versus mean period data can be converted to velocity versus depth data by computing wavelengths λ $(=V_p\bar{T})$ and using a "rule-of-thumb," such as the half-wavelength rule, to assign the velocity $V_p(\lambda)$ to a depth $\lambda/2$ (Chang and Ballard, 1973).*

117. A listing of DOMER is in Appendix H, and the input/output sequence is described below:

- _a_. Input the desired title.
- _b_. Input the geophone spacing.
- _c_. Input the time interval to be digitized, e.g., 300 msec.
- _d_. Digitize, using the cursor, the time interval, e.g., the 0- and 300-msec timing lines.
- _e_. Digitize zero time, i.e., either the 0-msec timing line or a time-break.
- _f_. Input the number of events (maximum of five) to be digitized.
- _g_. For each event:
  - (1) Input starting trace number.
  - (2) Digitize the arrival time of the event, peak, or trough on the starting trace.

---

* This is only an empirical procedure which should work best for sites where property variations are transitional in nature over the depth of investigation, i.e., not distinctly layered.

(3) Digitize peak or trough to left of event.

(4) Digitize peak or trough to right of event.

(5) Move to next trace and repeat steps.

(6) One button on the cursor is used for each of the following functions: (a) digitize point, (b) skip a trace, (c) redigitize preceding point, and (d) digitize the last point in an event.

(7) Repeat steps (1)-(6) for next event.

h. For each event a table is printed listing distance (X), arrival time (T), mean frequency (F), and group velocity (V_g = X/T) for each peak or trough in that event.

i. A time-distance plot for all the events is produced; the input is the same as for SEISPLOT, menu item (3).

Example 4

118. Figure 58 is a plot produced by DOMER of three events identified on a seismic refraction record from the same site as for the examples in Figures 53 and 57. Phase velocities for the events are indicated in Figure 58. Tabular output for event I is given in Figure 59.

Computer Modeling and Interpretation of Seismic Refraction Data

119. Two problems can be identified related to the seismic refraction method: (a) the direct problem, and (b) the inverse problem. The direct problem involves the determination of arrival times as a function of distance from a hypothetical source for various seismic events and a specified model; the model consists of layer velocities, layer thicknesses, and interface dips. For a given set of arrival time versus distance data from a refraction survey, the inverse problem involves the determination of the parameters of a subsurface model from the data itself. Two FORTRAN computer programs have been developed which solve the direct and inverse problems of the seismic refraction method, REFRDIR and REFRINV, respectively. REFRDIR is useful as a modeling tool for planning field surveys, e.g., geophone spacing and

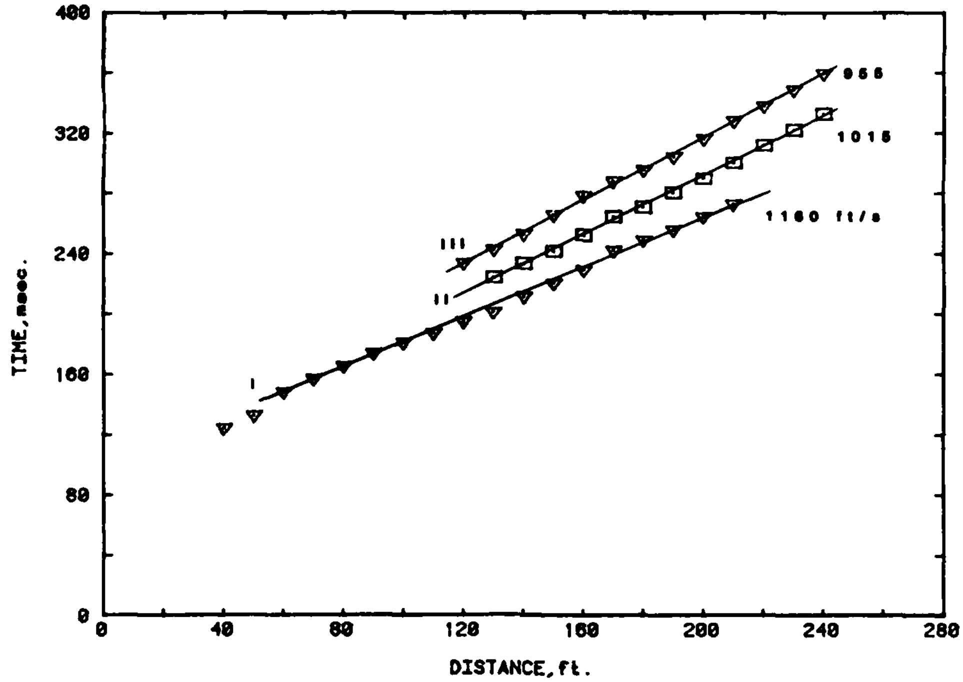

Figure 58. Plotted output from DOMER for three events identified in the Rayleigh wave train on a seismic refraction record

EVENT NUMBER 1

X, ft	T, msec	F, hz	Vg, ft/s
10			
20			
30			
40	124.3	48.1	321.8
50	132.7	49.9	376.7
60	148.5	57.7	404
70	157.2	56.9	445.2
80	165.6	48.7	483
90	174	48.7	517.2
100	181.2	40.8	551.8
110	187.6	39.6	586.3
120	195.3	38.8	614.4
130	201.4	38.5	645.4
140	211.6	40	661.6
150	220.2	40.8	681.1
160	229.4	47.5	697.4
170	242.5	44.9	701
180	249.4	43	721.7
190	256.3	39.2	741.3
200	265	38.5	754.7
210	273.1	37.1	768.9
220			
230			
240			

Figure 59. Tabular output from DOMER for Event I in Figure 58

survey line length required to investigate a possible subsurface model. REFRINV is very useful for refraction interpretation, where the data indicate the possibility of multiple, dipping layers.

120. The theoretical basis for the two programs (REFRDIR and REFRINV) is a set of equations relating to refracted waves (see, for example, Officer, 1957). These equations are given in the following sections describing the programs. They consist of: an equation for the horizontal phase velocity at the surface, equations corresponding to Snell's law at each interface, and an equation to compute the intercept times for the refracted waves.

121. Because the layer interfaces are assumed to be planar, the travel time for the wave refracted along the n^{th} interface (or top of the n^{th} layer) is given by

$$t_n(x) = T_{o,n} + x/v_n \tag{14}$$

Thus, given the horizontal phase velocity, v_n, and the intercept time, $T_{o,n}$ for the n^{th} refraction, the travel time can be computed at all source-to-receiver distances, x.

REFRDIR

122. The horizontal phase velocity and the intercept time are computed for each refraction event using the program REFRDIR. In this case, the P-wave velocities, the interface dips, and the layer "thicknesses" must be given. This program gives the intercept times and the horizontal phase velocities for both the direct and the reverse profile. The reverse profile is that array layout in which the shot is on the opposite end of the array relative to the direct profile.

123. In computing the intercept times and the horizontal phase velocities, program REFRDIR uses the angles, $\theta^{\pm}_{in}$, that the rays make with the normals to the interface. These angles, as well as other important parameters (for example, the layer "thicknesses"), are illustrated in Figure 60.

124. REFRDIR is a modeling program. It assumes: (a) that the velocity variation in the earth increases monotonically with depth,

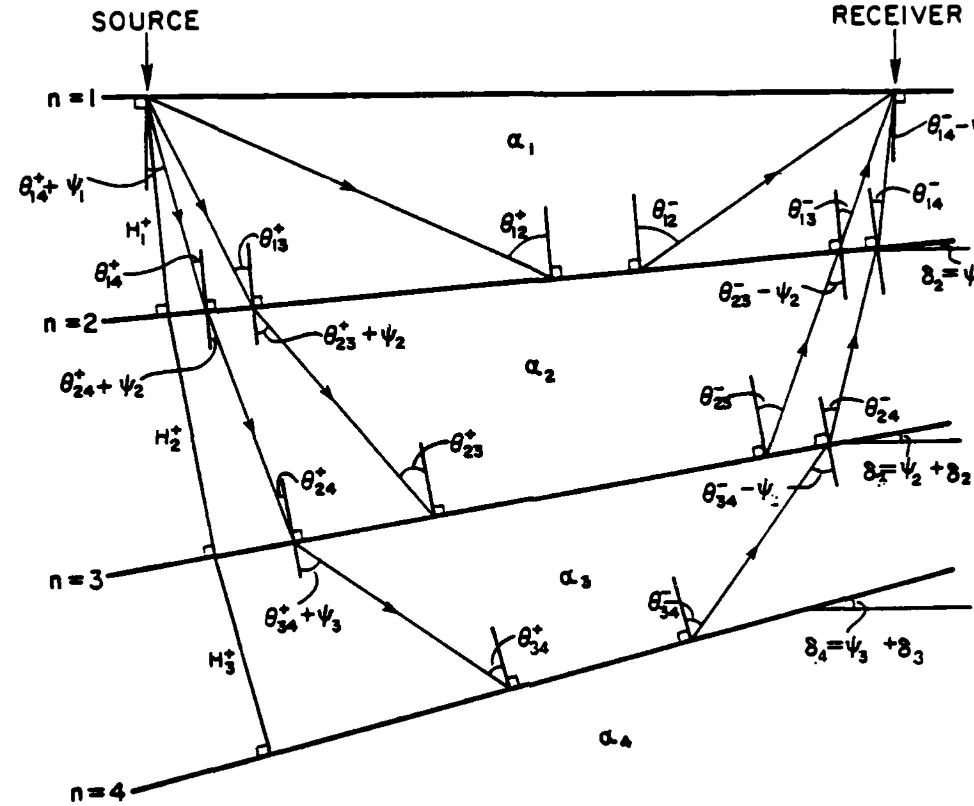

Figure 60. Assumed geometry for seismic refraction paths in common-strike, multiple dipping layers

(b) that it can be approximated by layers of constant velocity but with varying thicknesses, (c) that the interfaces between the layers are planar, and (d) that the interfaces have the same strike (see Figure 60). If REFRDIR is given an input model containing a velocity inversion (i.e., a decrease in velocity with depth), it will print an error message to that effect and stop.

125. The input data for the program are: (a) the number of layers in the model, (b) the layer thicknesses relative to the direct- and reverse-profile shotpoints (HPLUS and HMINUS; see Figure 1), and (c) the dip angles of the interfaces. The air/ground interface is the first one and it is assumed to be horizontal. Any velocity and distance

units may be used, as long as they are consistent, but the (dip) angles must always be given in degrees. REFRDIR computes and prints out: (a) the intercept times, and (b) the horizontal phase velocities of the refractions from each interface for the direct and reversed profiles. The following equations are used by REFRDIR:

$$\sin \theta_{n-1,n} = \alpha_{n-1}/\alpha_n \tag{15}$$

$$\theta_{n-1,n} = \theta^{\pm}_{n-1,n} = \theta^{-}_{n-1,n} \tag{16}$$

$$\sin \theta^{\pm}_{i-1,n} = (\alpha_{i-1}/\alpha_i) \sin (\theta^{\pm}_{i,n} \pm \psi_i) \tag{17}$$

$$v^{\pm}_n = \alpha_1/\sin(\theta^{\pm}_{1,n} \pm \psi_1) \tag{18}$$

$$T^{\pm}_{on} = (2H^{\pm}_{n-1}/\alpha_{n-1})\cos \theta_{n-1,n} + \sum_{i=1}^{n-2} (H^{\pm}_i/\alpha_i) (\cos \theta^{+}_{i,n} + \cos \theta^{-}_{i,n}) \tag{19}$$

The α's are the layer velocities, the H's are the layer thicknesses, the v's are the horizontal phase velocities, and the T's are the intercept times. The superscripts + or - refer to the direct and reversed profiles, respectively. See Figure 60 for the indexing and angle definitions.

126. For a given layer, computation is started by using Equation 15 to solve for $\sin \theta_{n-1,n}$. This, in turn, is used in Equation 17 to generate $\sin \theta^{\pm}_{n-2,n}$ through $\sin \theta^{\pm}_{1,n}$. The phase velocities and intercept times are then computed using Equations 18 and 19. To clarify the use of these equations, the calculations for the general case of three interfaces have been carried out in Appendix I. A listing of REFRDIR is also given in Appendix I.

127. Input. REFRDIR is extensively documented and prompting messages appear before each input. All input is in free-field format. The input sequence is given below:

Input No. 1: NLAYRS

NLAYRS--numbers of layers in the model

Input No. 2: SPRDLN

SPRDLN--the spread length, i.e., the length of the refraction survey line

Input No. 3: (ALPHA(N), DELTA(N), HPLUS(N), N=1, NLAYRS)

ALPHA(N)--velocity in layer N

DELTA(N)--dip angle (in degrees) of the N^{th} interface, which is the top surface of layer N ; DELTA (1) = dip of ground surface of model = 0

HPLUS(N)--thickness of N^{th} layer for the direct profile (see Figure 60)

Input No. 3 is repeated for each layer.

Input No. 4:

Input "1" if only forward profile to be plotted, and input "2" to plot both forward and reverse profiles.

128. Output. REFRDIR output consists of tabulated and plotted versions of the results of the computation. The tabulated output gives the horizontal phase velocities (apparent velocities) and intercept times for the forward and reverse profiles. For the plotted output, the apparent velocities and intercept times are used to define line segments, and forward and reverse time-distance plots are produced. PLOT2 (Appendix B) is used to produce the plots.

129. Example. Figures 61 and 62 illustrate the use of REFRDIR to solve a direct seismic refraction problem. The hypothetical model is shown in Figure 61, and the spread length was selected as 150 m. Computed time intercepts, see Figure 62, are indicated on the plot in Figure 61. This example is important because it illustrates that intuitive predictions of interface dip from apparent velocities or of apparent velocities from dip may be incorrect. For the example in Figures 61 and 62, intuition and experience might lead one to expect that the apparent velocity in the forward direction for interface 3 would be greater than V_3 ; however, the results from REFRDIR (see Figure 62) show that this is not the case.

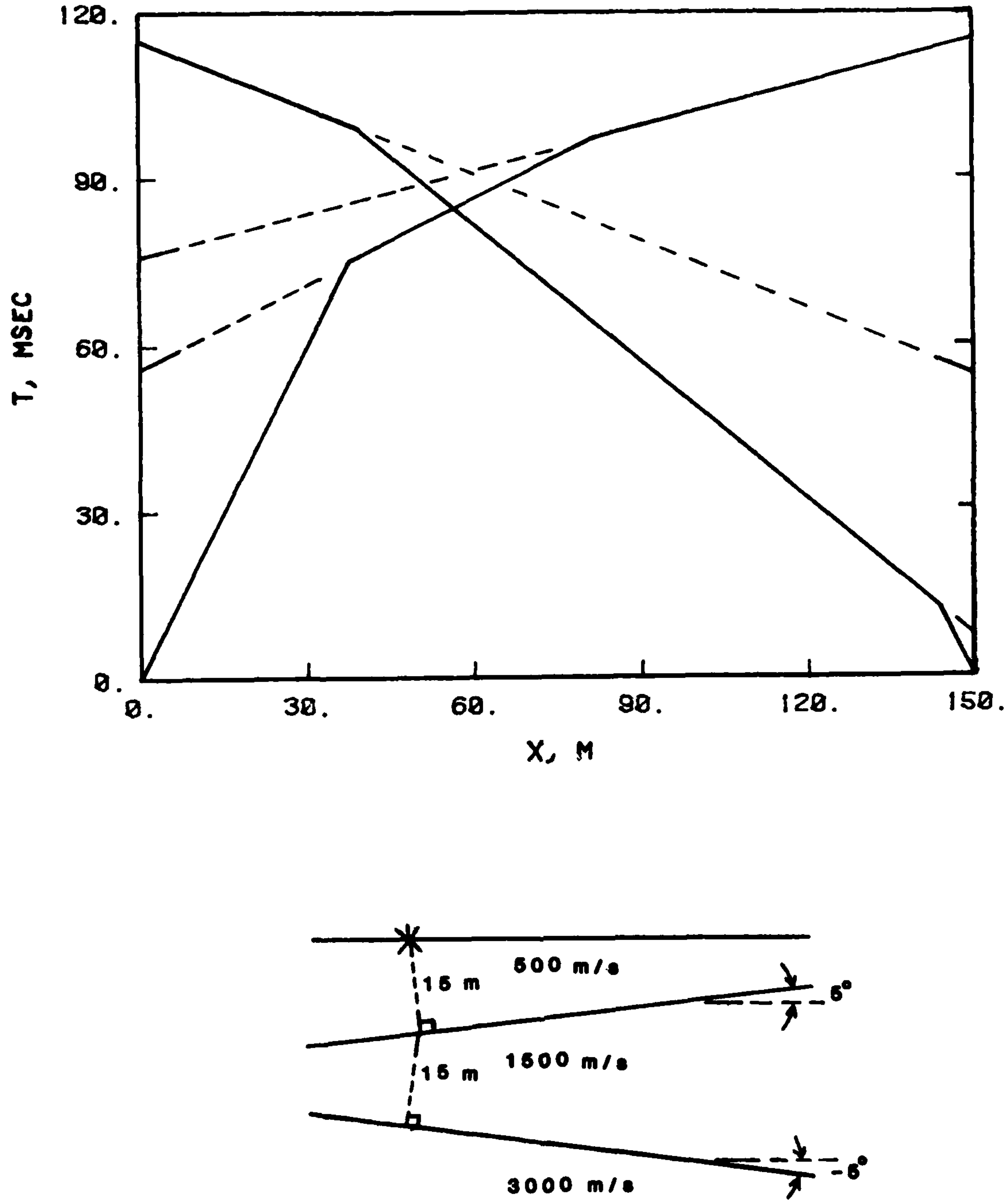

Figure 61. Three-layer model and first-arrival time-distance plot produced by REFRDIR

```
     INPUT NUMBER OF LAYERS IN MODEL
=3
     INPUT LENGTH OF SHOT SPREAD
=150
    FOR EACH LAYER INPUT A LINE ENTRY WITH THE FOLLOWING DATA
   SEPARATED BY COMMAS: LAYER VELOCITY,DIP OF INTERFACE,
   LAYER THICKNESS

=500,0,15
=1500,5,15
=3000,-5,
    VELOCITIES ARE IN METERS/SEC (OR FT/SEC), TIMES ARE IN
    MILLISECS AND LAYER THICKNESSES ARE IN METERS,(FT)

    THERE ARE  3 LAYERS IN THIS MODEL

    LAYER NO.    VELOCITY     DIP (DEGREES)    H+          H-

         1          500.           0.          15.0         2.0

         2         1500.           5.0         15.0        40.9

         3         3000.          -5.0
0

               *****  CALCULATED RESULTS  *****

    THE HORIZONTAL PHASE VELOCITIES AND THE INTERCEPT TIMES
    FOR THE DIRECT (+) AND REVERSED (-) PROFILES.

   INTERFACE NO.  PHASE VEL+   PHASE VEL-          T+          T-

         2          2000.851     1207.041           56.6         7.5

         3          3996.644     2497.997           76.4        55.1
    INPUT 1 IF YOU  WISH TO PLOT FORWARD
   PROFILE LINE ONLY
   ENTER 2 TO PLOT FORWARD AND REVERSEPROFILE
=2
```

Figure 62. Tabular output from REFRDIR for case shown in Figure 61

REFRINV

130. REFRINV uses the measured horizontal phase velocities (apparent velocities) and intercept times obtained from the direct and reversed profiles from refraction surveys to determine the velocities in the layers, the dip angles of the layer interfaces, and the layer "thicknesses." It is an inverse program, i.e., it gives, for its computed output, the parameters used as the input for the direct program, REFRDIR. On the other hand, the input of REFRINV corresponds to the output of REFRDIR.

131. This program uses the same equations that are used by REFRDIR. However, it uses them in opposite order to compute the physical properties of the medium by means of a "layer stripping" technique. That is, the program uses the measured data to find the properties of the first layer and then uses the measured data and the properties of the first layer to find the properties of the second layer and so on. REFRINV also uses the notation and the geometric parameters illustrated in Figure 60.

132. REFRINV has for its input: (a) the number of layers, (b) the velocity in the first layer, (c) the horizontal phase velocities and (d) the intercept times for the refracted waves from both the direct and reversed profiles. The program computes and prints out: (a) the velocity in each layer, (b) the layer "thicknesses," and (c) the dip of each interface (the first interface is the air/ground boundary and it is assumed to be horizontal). The phase velocities and layer velocities are given in metres/msec (ft/msec), the layer "thicknesses" are computed in metres (ft), and the dips in degrees. Like program REFRDIR, REFRINV assumes: (a) layer velocities increase monotonically with depth, (b) the velocity is constant in any given layer, and (c) interfaces are planar and have a common strike.

133. REFRINV makes use of the following equations (see Figure 60):

$$\theta^{\pm}_{i,n} \pm \psi_1 = \arcsin \left(\alpha_1 / V^{\pm}_n\right) \tag{20}$$

$$\theta^{\pm}_{m,n} + \psi_m = \arcsin \left[(\alpha_m/\alpha_{n-1}) \sin {}^{\pm}_{m-1,n}\right] \tag{21}$$

$$\alpha_{n-1}/\alpha_n = \sin\theta_{n-1,n};\ \theta^{+}_{n-1,n} = \theta^{-}_{n-1,n} = \theta_{n-1,n} \tag{22}$$

$$H^{\pm}_{n-1} = \frac{0.5\alpha_{n-1}}{\cos\theta_{n-1,n}} \left[T^{\pm}_{o,n} - \sum_{i=1}^{n-2} \frac{H^{\pm}_{i}}{\alpha_i} \left(\cos\theta^{+}_{i,n} + \cos\theta^{-}_{i,n}\right) \right] \tag{23}$$

$$\cos\theta_{n-1,n} = \left[1-(\alpha_{n-1}/\alpha_n)^2\right]^{1/2} \tag{24}$$

where the α's are the layer velocities, V's are the phase velocities, the T's are the intercept times, H's are the layer "thicknesses," and the ψ's are angles between interfaces.

134. Equations 20 through 24 are used iteratively: the input data for the second layer and the results from the first layer are used to find the results for the second layer; the input data for the third layer and results from the first and second layers are used to find the results for the third layer, and so on. This routine will become clearer after examination of Appendix J, where these equations are used in the general case of finding the velocities for four layers.

135. Input. The input to REFRINV is in free-field format and is summarized below:

Input No. 1: NLAYRS, V1

NLAYRS--number of layers (obtained as the number of straightline segments in the time-distance plot)

V1--true velocity of layer 1 (inverse slope of line segment passing through the origin of time-distance plot)

Input No. 2: (VPLUS(N), VMINUS(N), TPLUS(N), TMINUS(N), N=2, NLAYRS)

VPLUS(N), VMINUS(N)--forward and reverse apparent velocities respectively for the N^{th} interface

136. Output. The output of RESINV consists of two lists. The first list just summarizes the input data, while the second list presents

the calculated results: true layer velocities, interface dips, and layer thicknesses.

137. Example. Figure 63 is an example of the output of REFRINV. The input for this example is just the output from the REFRDIR example presented earlier in Figure 62. Note that the calculated results in Figure 63 agree with input model in Figure 62.

```
=3,.5
=2.000851,1.207041,56.6,7.5
=3.996644,2.497997,76.4,55.1
     VELOCITIES ARE IN METERS/MILLISEC. TIMES ARE IN MILLISEC
     AND LAYER THICKNESSES IN METERS

     NO. OF REFRACTIONS =  2; FIRST-LAYER VELOCITY IS:   0.500


     INPUT DATA:  PHASE VELOCITIES AND INTERCEPTS OF REFRACTIONS
     MEASURED ON DIRECT (+) AND REVERSED (-) PROFILES

    INTERFACE NO.  PHASE VEL+    PHASE VEL-      T+          T-

         2             2.001         1.207       56.6         7.5

         3             3.997         2.498       76.4        55.1


                  *****   CALCULATED RESULTS   *****
     THE WAVE VELOCITIES, INTERFACE DIPS AND LAYER THICKNESSES

      LAYER NO.     VELOCITY    DIP (DEG)    H+          H-
         1           0.500       0.          15.0         3.0
         2           1.500       5.0         14.9        40.9
         3           3.000      -5.0
```

Figure 63. Output from REFRINV using the calculated results in Figure 62 from REFRDIR as the input data

CROSSHOLE: Time-Sharing Version

138. The basic algorithms used by CROSSHOLE are documented in Butler, Skoglund, and Landers (1978); this basic documentation will not

be repeated here. Rather, the changes necessary to convert to remote-user or time-sharing operations are discussed and examples of the new input/output format are presented. The following four changes were made:

- a. Formatted input changed to allow free-field input.
- b. Input is from data files to avoid on-line input during program execution.
- c. Input sequence changed to eliminate redundant or duplicate input data.
- d. Considerable reformatting of program output to allow printing on 8.5-in.- (21.6-cm-) wide terminal paper.

CROSSHOLE is listed in Appendix K.

Input

139. All input is in free-field format and is from a data file (except Input No. 1 below). The input sequence and parameter descriptions are given below:

Input No. 1: DIN (1)

DIN (1)--name of input data file

Input No. 2: TITLE

TITLE--identification label for the crosshole data set

Input No. 3*: LIN, IOP1, N, IOP2, ISUM, M, DIST, AZIM, VFIRST, VLAST, DLLAST, IMAX, DELGS, IPUN

LIN--line number followed by blank

IOP1--input option code

1 for arrival times

2 for apparent velocities

3 for true velocity profile and arrival times

4 for true velocity profile and apparent

5 for true velocity profile

N--storage key for output options, dimensions profiles for summary tables

* The data file consists of line numbers followed by blanks, with data entries which follow on each line separated by blanks or commas as delimiters.

IOP2*output option code

0 Standard output, primarily for IOP1 = 1 or 2

1 For TABDUM, apparent velocity as a function of hole spacing

2 For SUMMARY table of three-hole set, P- and S-wave data

3 For SUMTWO comparison of computed apparent velocities with measured apparent velocities for known velocity profile

7 For carrying over the previous true velocity profile

ISUM--type of summary table. One for partial and two for full summary table

M--number of records per hold set

DIST--horizontal surface distance between boreholes

AZIM--hole pair aximuth, clockwise from north (in degrees)

VFIRST--first layer true velocity (if not defined by the data)

VLAST--deepest layer true velocity (if not defined by the data)

DLLAST--depth to deepest layer (if known)

IMAX--number of true velocity layers (for input options 3, 4, and 5)

DELGS--vertical geophone spacing (for input option 5 only)

IPUN--output punch option (for use with option 5)

Input No. 4: (LIN, SZ(J), SX(J), SY(J), GZ(J), GX(J), GY(J), J = 1, M)

LIN--line number followed by blank

SZ(J)--source depth of J^{th} record

SX(J)--source local x-derivation, from borehole survey (north direction positive)

SY(J)--source local y-deviation, from borehole survey (east direction positive)

---

* Currently, only the IOP2 = 0 option has been formatted for output on 8.5-in.-wide terminal paper. For all other output options, the output should be directed to a batch printer or wide-paper terminal.

GZ(J),GX(J),GY(J)--geophone/receiver depth, x , and y for J^{th} record

For IOP1 = 1 or 3

Input No. 5: (LIN, TR(J,N), J = 1,M)

LIN--line number followed by space

TR(J,N)--arrival time for J^{th} record

For IOP1 = 2 or 4

Input No. 5: (LIN, VA(J,N),J = 1,M)

LIN--line number

VA(J,N)--apparent velocity for J^{th} record

For IOP1 = 3, 4, or 5

Input No. 6: LIN, (DL(I,N) I = 1, IMAX-1)

LIN--line number

DL(IN)--thicknesses of specified true velocity layers

Input No. 7: LIN(VL(I,N), I = 1, IMAX-1)

LIN--line number

VL(I,N)--true velocities

Output

140. Three types of printed output are generated by CROSSHOLE: (a) a summary tabulation of the input data; (b) a list of caution and alternative interpretation messages; (c) a tabulation of the CROSSHOLE interpretation or calculation results.

Examples

141. Figure 64 is an example of input data file for a case where arrival times are input. Figure 65 is the output from CROSSHOLE for the input data file in Figure 64. The caution messages in Figure 65 call attention to the fact that many of the interface locations are poorly defined due to an insufficient number of apparent velocity values in each of the velocity zones or layers.

142. Typically all available information is utilized in developing representative velocity profiles for a site. Seismic refraction and uphole/downhole seismic results, if available, are examined. Also, any borehole log data are examined. Representative velocities which are

```
100                 - S-WAVE - D/S TOE - P TO 0 = 10 FT
110 1,,,,9,10.2,130,,,,,,,
120 5,-0.061,-0.093,5,-0.003,0.013
130 10 -0.055,-0.085,10,0.019,0.062
140 15 -0.160 -0.241 15 0.032 0.078
150 20 -0.078 -0.273 20 0.078 0.002
160 25 -0.110 -0.445 25 0.103 -0.047
170 30 -0.033 -0.530 30 0.192 -0.126
180 35 -0.060 -0.649 35 0.314 -0.165
190 40 -0.087 -0.729 40 0.424 -0.214
200 45 -0.102 -0.803 45 0.561 -0.230
210 14
220 13
230 15
240 18
250 15.5
260 15.5
270 14.5
280 16
290 16.5
```

Figure 64. Example of the format of an input data file for CROSSHOLE

finally accepted are "averaged" values of all values available. Interface depths are guided by borehole data if available.

ENTER THE NAME OF THE DATA FILE YOU WANT TO PROCESS
=CHAR?

CROSSHOLE DATA - S-WAVE - D/S TOE - P TO Q = 10 FT

HORIZONTAL DISTANCE BETWEEN HOLES IS 10.2

DEPTH SHOT	DEPTH GEO	DIRECT ARRIVAL DISTANCE	DIRECT ARRIVAL TIME	APPARENT VELO	SHOT HOLE X-DEV	SHOT HOLE Y-DEV	GEO HOLE X-DEV	GEO HOLE Y-DEV
5.0	5.0	10.2	0.0140	732.	-0.06	-0.09	-0.00	0.01
10.0	10.0	10.3	0.0130	790.	-0.06	-0.08	0.02	0.06
15.0	15.0	10.3	0.0150	680.	-0.16	-0.24	0.03	0.08
20.0	20.0	10.3	0.0150	573.	-0.08	-0.27	0.06	0.00
25.0	25.0	10.4	0.0155	669.	-0.11	-0.45	0.10	-0.05
30.0	30.0	10.4	0.0155	669.	-0.03	-0.53	0.19	-0.13
35.0	35.0	10.3	0.0145	714.	-0.06	-0.65	0.31	-0.16
40.0	40.0	10.3	0.0160	643.	-0.09	-0.73	0.42	-0.21
45.0	45.0	10.3	0.0165	621.	-0.10	-0.80	0.56	-0.23

CROSSHOLE DIAGNOSTIC - S-WAVE - D/S TOE - P TO Q = 10 FT

EXECUTION CHECK - LAYER 1 - DEPTH 1 - DOWN 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 6.0
COULD BE ANYWHERE BETWEEN 5.0 AND 10.0
EXECUTION CHECK - LAYER 2 - DEPTH 2 - UP 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 13.6
COULD BE ANYWHERE BETWEEN 10.0 AND 13.6
EXECUTION CHECK - LAYER 3 - DEPTH 3 - UP 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 16.4
COULD BE ANYWHERE BETWEEN 15.0 AND 18.4
EXECUTION CHECK - LAYER 4 - DEPTH 4 - DOWN 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 21.4
COULD BE ANYWHERE BETWEEN 21.4 AND 25.0
EXECUTION CHECK - LAYER 5 - DEPTH 6 - DOWN 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 30.9
COULD BE ANYWHERE BETWEEN 30.9 AND 35.0
EXECUTION CHECK - LAYER 6 - DEPTH 7 - UP 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 38.8
COULD BE ANYWHERE BETWEEN 35.0 AND 38.8
EXECUTION CHECK - LAYER 7 - DEPTH 8 - UP 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 44.3
COULD BE ANYWHERE BETWEEN 40.0 AND 44.3

CROSSHOLE INTERPRETATION - S-WAVE - D/S TOE - P TO Q = 10 FT

INTERFACE DEPTH GEO DEPTH	SHOT DEPTH	TRUE VELOCITY	COMPUTED TRAVEL TIMES, SECONDS DIRECT	DOWN 1LAYER	DOWN 2LAYER	DOWN 3LAYER	UP 1LAYER	APPARENT COMPUTED	APPARENT MEASURED
5.0	5.0	761.	0.0135			0.0363		**************	
10.0	10.0	761.	0.0135			0.0293		**************	
< 13.6									
15.0	15.0	680.	0.0150		0.0232	0.0332	0.0152	668.	688.
< 15.4									
20.0	20.0	573.	0.0180	0.0180	0.0273		0.0180	573.	573.
< 21.4									
25.0	25.0	669.	0.0155	0.0207				669.	669.
30.0	30.0	669.	0.0155	0.0155				669.	669.
< 30.9									
35.0	35.0	714.	0.0145					714.	714.
< 38.9									
40.0	40.0	643.	0.0160				0.0160	643.	643.
< 44.3									
45.0	45.0	621.	0.0165				0.0165	621.	621.

MEAN DIFFERENCE = 0.03 *
STANDARD DEVIATION OF DIFFERENCE = 1.91 *

* PERCENT OF MEASURED VELOCITY

Figure 65. Output from CROSSHOLE for the input data file shown in Figure 64

PART V: SUMMARY AND FUTURE PLANS

Summary

143. This report presents the results of an effort directed to the improvement of geophysical data acquisition, processing, and interpretation. The major part of the work involves the adaptation of existing or development of new computer programs for processing and interpreting geophysical data. Some of the work can be described as new and, perhaps, innovative, while other parts of the work involve the implementation of existing or state-of-the-art techniques to Corps of Engineers geotechnical applications. The result is the compilation of a rather diverse group of computer programs and methodologies for the electrical resistivity, microgravimetric, and seismic methods.

144. Three computer programs for processing and interpreting electrical resistivity data are presented and documented. RESDIR and RESINV are programs for use with vertical resistivity sounding surveys. For a given model of subsurface resistivity variations, RESDIR computes the apparent resistivity as a function of electrode spacing for an expanding electrode array; this capability is useful for predicting the response or applicability of resistivity soundings to a suspected or postulated resistivity variation. RESINV attempts to determine a "best-fit" subsurface resistivity model directly from the field data; some expertise is required on the part of the interpreter in specifying an initial or "best-guess" model for input to the program. RESDAT is a general purpose resistivity data processing program. Both vertical sounding and horizontal profiling survey data can be handled by RESDAT; and for the case of vertical sounding data, an option is available for interpreting the processed data using a subroutine version of RESINV.

145. Three computer programs are documented for use in connection with microgravity surveys (actually the programs and techniques can be with gravity surveys on any scale). TIDES computes the theoretical earth-tide variation at any location and is used in conjunction with base station reoccupations to assure consistent gravimeter performance

during field surveys. The program TALGRAD computes gravity and gravity-gradient profiles across two-dimensional models. HILBERT computes the Hilbert transform of a discrete profile data set; if the profile data set is the horizontal gravity-gradient profile over a two-dimensional structure, then the Hilbert transform profile will be the vertical gravity gradient. In addition to the three computer programs, two microgravity survey methodologies are presented: (a) a technique for reduction of errors in microgravity surveying by the use of optimal gravity station occupation schemes; and (b) the use of polynomial surface fitting for determining the regional field component in a set of data.

146. Several computer programs for processing and interpreting seismic refraction and crosshole survey data are documented. Four programs are presented for digitizing, processing, and interpreting seismic refraction analog field data; use of these programs considerably expedites the processing of refraction data. Two programs are presented for interpretation of seismic refraction data, REFRDIR and REFRINV. The program REFRDIR computes first-arrival, time-distance data for a specified subsurface velocity model. REFRINV determines parameters of a subsurface velocity model, consisting of layer thicknesses and velocites, directly from processed field data. Finally, changes made to the program CROSSHOLE are documented. Specifically, CROSSHOLE can now be executed from time-sharing terminals.

147. Examples of the use of each of the computer programs are presented. Some of the examples are quite brief. Also, some of the examples appear in other reports in greater detail (see Preface and Part I for discussion of companion research efforts). However, some of the examples are presented in a detailed fashion and appear here for the first time.

Future Plans

148. Recommendations for future work to further automate geophysical data processing and interpretation in support of geotechnical

investigations are listed below:

a. Obtain microcomputer for use in the field and convert RESDIR, RESINV, and RESDAT to execute on it; this will make available in the field rigorous resistivity sounding interpretations.

b. Pursue the development of automated pole-dipole resistivity data processing and interpretation techniques.

c. Acquire or develop a computer program for automatically computing terrain corrections to microgravity survey data.

d. Develop a general purpose microgravity data-processing program for use with field microcomputers.

e. Initiate field digital recording of seismic data to eliminate the necessity of "picking" field analog records.

f. Initiate data-processing techniques on field microcomputer systems.

g. Incorporate rigorous seismic interpretation procedures in conjunction with data-processing techniques.

REFERENCES

Bates, E. F. 1973. "Detection of Subsurface Cavities," Miscellaneous Paper S-73-40, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Bristow, C. M. 1966. "A New Graphical Resistivity Technique for Detection of Air-Filled Cavities," Studies in Speleology, Vol 7, Part 4, pp 204-227.

Butler, D. K. 1980a. "Microgravimetric Techniques for Geotechnical Applications," Miscellaneous Paper GL-80-13, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Butler, D. K. 1980b. "Microgravimetry and the Measurement and Application of Gravity Gradients," Proceedings of the Army Science Conference, West Point, N. Y.

Butler, D. K. 1980c. "Site Investigations in Karst Regions--Microgravimetric and Electrical Resistivity Methods," 50th International Meeting of the Society of Exploration Geophysicists, Houston, Tex., Abstract in Geophysics, Vol 46, No. 4, p 452.

Butler, D. K. 1980d. "Assessment of Microgravimetric Techniques for Site Investigations," 49th International Meeting of the Society of Exploration Geophysicists, New Orleans, La., Abstract in Geophysics, Vol 45, No. 4, p 549.

Butler, D. K. in press. "Cavity Detection and Delineation Research, Report 1, Microgravimetric and Magnetic Surveys-Medford Cave Site, Florida," U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Butler, D. K., Whitten, C. B., and Smith, F. L. in press. "Cavity Detection and Delineation Research; Report 4, Microgravimetric Survey-Manatee Springs, Florida," U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Butler, D. K., and Curro, J. R., Jr. 1981. "Crosshole Seismic Testing: Procedures and Pitfalls," Geophysics, Vol 46, pp 23-29.

Butler, D. K., and Murphy, W. L. 1980. "Evaluation of Geophysical Methods for Cavity Detection at the WES Cavity Test Facility," Technical Report GL-80-4, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Butler, D. K., Skoglund, G. R., and Landers, G. B. 1978. "Crosshole: An Interpretive Computer Code for Crosshole Seismic Test Results, Documentation, and Examples," Miscellaneous Paper S-78-8, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Chang, F. K., and Ballard, R. F., Jr. 1973. "Rayleigh-Wave Dispersion Technique for Rapid Subsurface Exploration," Miscellaneous Paper S-73-20, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Coons, R. L., Wooland, G. P., and Hershey, G. 1967. "Structural Significance of the Mid-Continent Gravity High," Journal of the American Association of Petroleum Geologists, Vol 51, pp 2381-2409.

Cooper, S. S., and Bieganousky, W. A. 1978. "Geophysical Survey of Cavernous Areas, Patoka Dam, Indiana," Miscellaneous Paper S-78-1, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Cordell, L. 1970. "Iterative Three-Dimensional Solution of Gravity Anomaly Data," Report No. USGS-GD-71-001, U. S. Geological Survey.

Davis, P. A. 1979a. "Development and Application of Resistivity Sounding Inversion for Several Field Arrays," M.S. Thesis, University of Minnesota, Minneapolis, Minn.

__________. 1979b. "Interpretation of Resistivity Sounding Data-Computer Programs for Solutions to the Forward and Inverse Problems," Information Circular 17, Minnesota Geological Survey, St. Paul, Minn.

Department of the Army. 1979. "Geophysical Exploration," Engineer Manual EM 1110-1-1802, Office, Chief of Engineers, Washington, D. C.

Dobrin, M. B., Simon, R. F., and Lawrence, P. L. 1951. "Rayleigh Waves from Small Explosions," Transactions, American Geophysical Union, Vol 32, pp 822-832.

Erdelyi, A. 1954. "Tables of Integral Transforms," McGraw-Hill, New York, N. Y.

Ewing, W. M., Jardetzky, W. S., and Press, F. 1957. "Elastic Waves in Layered Media," McGraw-Hill, New York, N. Y.

Fountain, L. S. 1975. "Evaluation of High-Resolution Earth Resistivity Measurement Techniques for Detecting Subsurface Cavities in a Granite Environment," Final Report, Project No. 14-4250, Southwest Research Institute, San Antonio, Tex.

Fountain, L. S., Herzig, F. X., and Owen, T. E. 1975. "Detection of Subsurface Cavities by Surface Remote Sensing Techniques," Report No. FHWA-RD-75-80, Federal Highway Administration, Washington, D. C.

Fountain, L. S., and Herzig, F. X. 1980. "Earth Resistivity and Hole-to-Hole Electromagnetic Transmission Tests at Medford Cave, Florida," Final Technical Report, SwRI Project 14-5940, Southwest Research Institute, San Antonio, Tex.

Franklin, A. G., Patrick, D. M., Butler, D. K., Strohm, W. E., and Hynes-Griffin, M. E. 1981. "Foundation Considerations in Siting of Nuclear Facilities in Karst Terrains and Other Areas Susceptible to Ground Collapse," NUREG/CR-2062, U. S. Nuclear Regulatory Commission, Washington, D. C.

Fugro National, Inc. 1980. "MX Siting Investigation Survey--Dry Lake Valley," Technical Report FN-TR-33-DL, Long Beach, Calif.

Garland, G. D. 1977. The Earth's Shape and Gravity, Pergamon Press, N. Y.

Ghosh, D. 1971a. "Application of Linear Filter Theory to the Direct Interpretation of Geoelectrical Resistivity Sounding Measurements," Geophysical Prospecting, Vol 19, pp 192-217.

__________. 1972b. "Inverse Filter Coefficients for the Computation of Apparent Resistivity Standard Curves for Horizontally Layered Earth," Geophysical Prospecting, Vol 19, pp 769-775.

Grant, F. S. and West, G. F. 1965. "Interpretation Theory in Applied Geophysics," McGraw-Hill, New York, N. Y.

Hubbert, M. K. 1948. "A Line Integral Method of Computing the Gravimetric Effects of Two-Dimensional Masses," Geophysics, Vol 13, pp 215-225.

Keller, G. V., and Frischknecht, F. C. 1966. Electrical Methods in Geophysical Prospecting, Pergamon Press, New York, N. Y.

Longman, I. M. 1959. "Formulas for Computing the Tidal Acceleration Due to the Moon and Sun," Journal of Geophysical Research, Vol 64, pp 2351-2355.

Marquardt, D. W. 1963. "An Algorithm for Least-Squares Estimation of Nonlinear Parameters," Journal of the Society of Industrial and Applied Mathematics, Vol 11, pp 431-441.

McConnell, R., Hearty, D., and Winter, P. 1974. "An Evaluation of the LaCoste and Romberg Model-D Microgravimeter," Seventh Meeting of the International Gravity Commission, Paris.

McLamore, V. R., and Walen, P. A. 1979. "A Gravity Study of an Alluvial Basin," Geophysical Methods in Geotechnical Engineering, Proceedings of the American Society of Civil Engineers Annual Meeting, Atlanta, Ga.

Merrick, N. P. 1977. "A Computer Program for the Inversion of Schlumberger Sounding Curves in the Apparent Resistivity Domain," Water Research Committee Hydrogeological Report No. 1977/5, New South Wales, Australia.

Mooney, H. M. 1979. "Handbook of Engineering Geophysics, Volume 2--Electrical Resistivity," Bison Instruments, Inc., Minneapolis, Minn.

Moore, R. W. 1945. "An Empirical Method of Interpretation of Earth Resistivity Methods," Transactions of the American Institute of Mining and Metallurgical Engineers, Vol 164, pp 197-223.

Officer, C. B. 1957. Introduction to the Theory of Sound Transmission, McGraw-Hill, New York, N. Y.

Redpath, B. B. 1973. "Seismic Refraction Exploration for Engineering Site Investigations," Technical Report E-73-4, U. S. Army Engineer Waterways Experiment Station, CE, Livermore, Calif.

Sanker Narayan, P. V., and Ramanujachary, K. R. 1967. "An Inverse Slope Method of Determining Absolute Resistivity," Geophysics, Vol 32, pp 1036-1040.

Shuey, R. T. 1972. "Application of Hilbert Transforms to Magnetic Profiles," Geophysics, Vol 37, pp 1043-1045.

Spiegel, R. J., Sturdivant, V. R., and Owen, T. E. 1980. "Modeling Resistivity Anomalies from Localized Voids Under Irregular Terrain," Geophysics, Vol 45, pp 1164-1183.

Talwani, M., Werzel, J. L., and Landisman, M. 1959. "Rapid Gravity Computations for Two-Dimensional Bodies with Application to the Mendocine Submarine Fracture Zones," Journal of Geophysical Research, Vol 64, pp 49-59.

Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A. 1976. "Applied Geophysics," Cambridge University Press, New York, N. Y.

Tracey, F. T. 1974. "A Computer Program for Contouring the Output of Finite Element Programs," Miscellaneous Paper K-74-1, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Zohdy, A. A. R., Eaton, G. P., and Mabey, D. R. 1974. "Application of Surface Geophysics to Ground Water Investigations," U. S. Geological Survey, Techniques of Water Resources Investigations, Book 2, Chapter D1.

APPENDIX A: RESDIR LISTING


```
** RUN *;ROSD441/PLOTS,E;ROSD441/PLOTLL,E
      INTEGER E
      COMMON/Z1/E,M,N/Z2/DELX,SPAC
      COMMON/ZA3/P(99)/ZA4/R(134)
      DIMENSION FLTR1(29),FLTR2(34)
      DIMENSION SN(30),R1(31),ASP(100)
      DATA(FLTR1(I),I=1,29)/.00046256,-.0010907,.0017122,-.0020687,
     &.0043048,-.0021236,.015995,.017065,.098105,.21918,.64722,1.1415,
     &.47819,-3.515,2.7743,-1.201,.4544,-.19427,.097364,-.054099,.031729
     &,-.019109,.011656,-.0071544,.0044042,-.002715,.0016749,-.0010335,
     &.00040124/
      DATA(FLTR2(I),I=1,34)/.000238935,.00011557,.00017034,.00024935,
     &.00036665,.00053753,.0007896,.0011584,.0017008,.0024959,.003664,
     &.0053773,.007893,.011583,.016998,.024934,.036558,.053507,.078121,
     &.11319,.16192,.22363,.28821,.30276,.15523,-.32026,-.53557,.51787,
     &-.196,.054394,-.015747,.0053941,-.0021446,.000665125/
C
C  INPUT NO. 1   ARRAY CHOICE, INPUT-
C        1--FOR SCHLUMBERGER,
C         2--FOR WENNER,
C         3--FOR BIPOLE-BIPOLE,
C  INPUT NO. 2   SPAC,E,M           (FORMAT-FREE)
C         SPAC = CLOSEST A OR S SPACING (REAL)
C         E    = NUMBER OF MODEL LAYERS (INTEGER)
C        M     = NUMBER OF FIELD READINGS (INTEGER) , 6/DECADE
C  INPUT NO. 2A ENTER ONLY FOR BIPOLE-BIPOLE ARRAY, INPUT-
C        1--IF N-VALUES ARE VARIED,
C         0--IF A-SPACINGS ARE VARIED,
C  INPUT NO. 2B ENTER ONLY FOR BIPOLE-BIPOLE, IF VALUE ENTERED IN 2A WAS-
C        1--INPUT N-VALUES (TOTAL M) IN INCREASING ORDER (FORMAT-FREE)
C         0--INPUT ONE N-VALUE. (N.NE.1)
C  INPUT NO. 3   ENTER LAYER PARAMETERS. (TOTAL 2E-1, FORMAT-FREE)
C         ORDER-- H(1),H(2),...,H(E-1),R(1),R(2),...,R(E)
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C  REPEAT FOR ADDITIONAL MODELS.
C
    1 FORMAT(V)
      PRINT,'INPUT NO. 1---INDEX (ARRAY TYPE)'
 1000 READ 1, INDEX
      IF(INDEX.EQ.0) STOP
      PRINT, 'INPUT NO. 2---SPAC,E,M'
      READ 1, SPAC,E,M
      IF(INDEX-2) 40,40,5
    5 READ 1,IX
      IF(IX.EQ.1) GO TO 20
      J=1
      GO TO 35
   20 J=M
   35 READ 1, (SN(I),I=1,J)
   40 N=2*E-1
      SPAC=ALOG(SPAC)
      PRINT, 'INPUT NO. 3, MODEL PARAMETERS, THICKNESSES(H) AND
     & RESISTIVITIES(R)---H(1),H(2), . . . ,H(E-1),R(1), . . . ,R(E)'
      READ 1,(P(I), I=1,N)
      PRINT 42
```

```
 42 FORMAT(//" APPARENT RESISTIVITY VALUES")
    IF(INDEX-2)43,45,47
 43 PRINT 44
 44 FORMAT(/" SCHLUMBERGER ARRAY"//)
    GO TO 50
 45 PRINT 46
 46 FORMAT(/" WENNER ARRAY"//)
    GO TO 50
 47 PRINT 48
 48 FORMAT(/" BIPOLE-BIPOLE ARRAY"//)
 50 DELX = ALOG(10.)/6.
    IF(INDEX-2) 70,80,300
 70 Y=SPAC-19.*DELX-0.13069
    DO 75 I=1,M+28
       CALL TRANSFM(Y,I)
 75    Y=Y+DELX
    CALL FILTER(FLTR1,29)
    GO TO 120
 80 S=ALOG(2.)
    Y=SPAC-10.8792495*DELX
    DO 110 I=1,M+33
       CALL TRANSFM(Y,I)
       A=R(I)
       Y1=Y+S
       CALL TRANSFM(Y1,I)
       R(I)=2.*A-R(I)
110    Y=Y+DELX
    GO TO 119
300 M1=1
    IF(LX.NE.1) GO TO 111
    M1=M
    M=1
111 DO 117 I=1,M1
       Y=SPAC-10.8792495*DELX
       A=SN(I)
       A1=ABS(A-1.)
       S1=ALOG(A1)
       IF(A.LT.1.) Y=Y-ALOG(A)
       B=1.
       IF(A.LT.1.) B=A*A+A-1.
       S2=ALOG(A)
       S3=ALOG(A+1.)
    DO 116 J=1,M+33
          Y1=Y+S1
           CALL TRANSFM(Y1,J)
           AA=R(J)/A1
           Y1=Y+S2
           CALL TRANSFM(Y1,J)
           AA=AA-2.*R(J)/A
           Y1=Y+S3
           CALL TRANSFM(Y1,J)
           R(J)=(AA+R(J)/(A+1.))*A*(A+1.)*A1/(2.*B)
 116       Y=Y+DELX
        IF(IX.NE.1) GO TO 117
        CALL FILTER(FLTR2,34)
```

```
          R1(I)=R(I)
    117   CONTINUE
      IF(M.NE.1) GO TO 119
      M=M1
      GO TO 120
  119 CALL FILTER(FLTR2,34)
  120 PRINT 125,E
  125 FORMAT(/I3," LAYER MODEL.")
      PRINT 130
  130 FORMAT(/5X,"LAYER NO.",3X,"THICKNESS",3X,"RESISTIVITY"/)
      DO 140 I=1,E-1
          J=I
      PRINT 135,J,P(I),P(I+E-1)
  135     FORMAT(9X,I2,5X,F8.3,7X,F8.3)
  140     CONTINUE
      PRINT 145,E,P(N)
  145 FORMAT(9X,I2,20X,F8.3)
      IF(INDEX-2) 205,205,150
  150 IF(IX.NE.1) GO TO 190
      SP=EXP(SPAC)
      PRINT 160,SP
  160 FORMAT(/" BIPOLE A-SPACING =",F6.2)
      PRINT 170
   170 FORMAT(//10X,"N",9X,"RHO"/)
      DO 185 I=1,M
      PRINT 180,SN(I),R1(I)
  180     FORMAT(7X,F7.2,3X,F9.3)
  185 CONTINUE
      GO TO 240
  190 PRINT 200,SN(1)
  200 FORMAT(/" BIPOLE N-SPACING =",F6.2)
  205 PRINT 210
   210 FORMAT(//7X,"SPACING",7X,"RHO"/)
      X=SPAC
      DO 230 I=1,M
          ASP(I)=EXP(X)
      PRINT 220, ASP(I),R(I)
  220     FORMAT(6X,F7.2,3X,F9.3)
  230     X=X+DELX
      PRINT, 'DO YOU WANT DATA PLOTS YES(1), NO(2)'
      READ 1, II
      IF(II.EQ.2) GO TO 240
      PRINT, 'LINEAR(1) OR LOG-LOG(2)'
      READ 1, JJ
      IF(JJ.EQ.2) GO TO 235
      CALL PLOT2(ASP,R,M)
      GO TO 240
  235 CALL PLOTLL(ASP,R,M)
  240 GO TO 1000
      END
      SUBROUTINE TRANSFM(Y,I)
      INTEGER E
      COMMON/Z1/E,M,N
      COMMON/ZA3/P(99)/ZA4/R(134)
      DIMENSION T(50)
```

```
      U=1./EXP(Y)
      T(1)=P(N)
      DO 30 J=2,E
         A=EXP(-2.*U*P(E+1-J))
         B=(1.-A)/(1.+A)
         RS=P(N+1-J)
         TPR=RS*B
         T(J)=(TPR+T(J-1))/(1.+TPR*T(J-1)/(RS*RS))
   30    CONTINUE
      R(I)=T(E)
      RETURN
      END
      SUBROUTINE FILTER(FLTR,K)
      INTEGER E
      COMMON/Z1/E,M,N
      COMMON/ZA4/R(134)
      DIMENSION RES(31),FLTR(K)
      DO 20 I=1,M
         RE=0
      DO 10 J=1,K
            B=FLTR(J)*R(I+K-J)
   10       RE=RE+B
   20    RES(I)=RE
      DO 30 I=1,M
   30    R(I)=RES(I)
      RETURN
      END
```

APPENDIX B: PLOT2 AND PLOTLL INPUT INSTRUCTIONS AND LISTINGS

Instructions for PLOT2

All input is in free-field format, and the program will call for the variables by name. The plot specification input variables are indicated in Figure B1.

Input No. 1: XØ, YØ, SFX, SFY, IA, IDASH, THETA

XØ,YØ--X and Y coordinates of the origin on the paper, in inches from the lower left of plotting surface

SFX,SFY--scale factors in the X and Y directions, respectively, in user units per inch of plot

IA--axes specification;

0--X and Y axes drawn

1--no axes drawn

2--X and Y axes drawn plus lines to form right and top border

IDASH--=0, plots solid line connecting data points, ≠0, plots dashed line

THETA--angle in degrees between X-axis and long axis of plotter, counterclockwise positive

Input No. 2: HTX, XL, XS, NDX, N_X, SPX, ITX

HTX--height of characters in inches (0.1 is typical) for X-axis

XL--length of X-axis in inches

XS--starting point of X-axis from origin (X0) in inches

NDX--number of digits to right of decimal in axes labels

NPX--power of 10 by which the scale is to be multiplied

SPX,ITX--input 0 for both

Input No. 3: HTY, YL, YS, NDY, NPY, SPY, ITY

Exactly analogous to Input No. 2 except for Y-axis.

Input No. 4: X-LABEL

Input title of X-axis

Input No. 5: Y-LABEL

Title for Y-axis

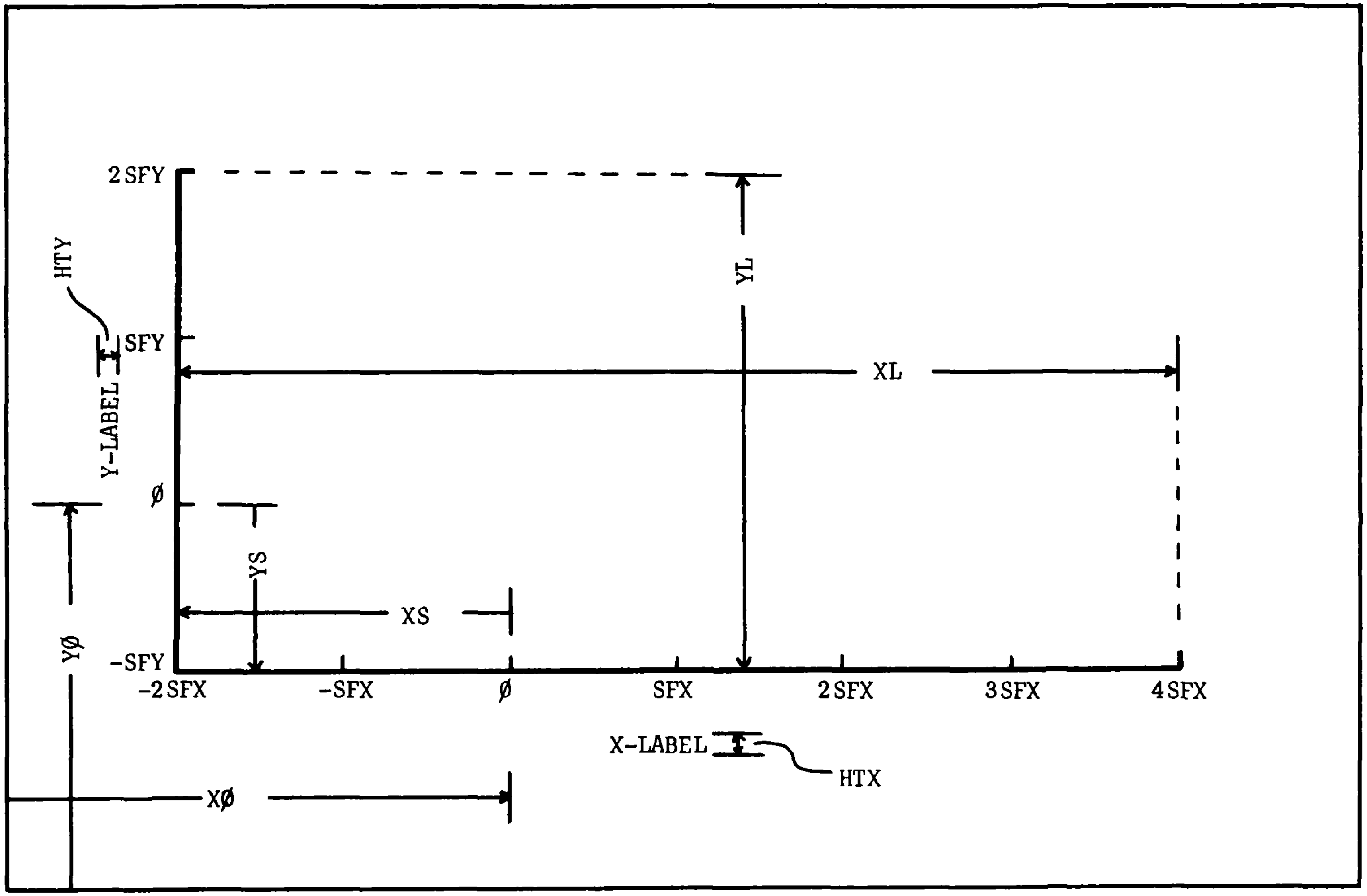

Figure B1. Definition of plot specification input parameters for PLOT2. XØ, YØ, XS, YS, XL, and YL are in inches. SFX and SFY are in user units per inch.

Input No. 6: SL1, SL2, BL

Input only if IDASH $\neq$ 0

SL1, SL2, BL--length of dashes and blank in inches (two different dash lengths, if desired, with constant blank length)

```
C    **** SUBROUTINE FOR TEKTRONIX 4662 DIGITAL PLOTTER ******
          SUBROUTINE PLOTS(IDT)
          CHARACTER *10 FMT/10H(156A1,I4)/,IASC*4
          DIMENSION KP(156),IBCD(1),IASB(2),IOUT(32),ITAB(4,16)
          INTEGER HIY,HIYP,XLOY,XLOYP,HIX,HIXP
          LOGICAL L1,L3
          DATA C1,C2,C3 /0.46875,0.01464844,0.00366211/
          DATA IC1,IC2,IC3,IC4,IC5 /134217728,262144,512,128,4/
          DATA IESC,IE,IGS /3623878656,35328,3692314112/
          DATA KP(1),KP(3),IRPH /3623878656,5368709120,5502926848/
          CALL FPARAM(1,160)
          ID = IDT
          IF(ID-69) 2,2,1
        1 ID = ID/IC1
        2 KP1 = IESC+ID*IC2+IE+29
          KP2 = KP1+6644 ; KP3 = KP1+8675 ; KP4 = KP1+1507
          PRINT 120,KP1,KP2,KP4,160,KP3
          KP(2) = ID*IC1 ; KP(4) = IESC
          KP(5) = KP(2) ; KP(6) = 75*IC1
          ICI = 108+ID ; IK = 7 ; IC = ICI+102+ID
          KP1 = KP1+483 ; KP2 = KP1+4096
          L2 = 1
          HXF = .01111111 ; HYF = 446.7273
          HIYP = 0 ; XLOYP = 0 ; HIXP = 0
          HIXP = 0 ; LOXP = 0 ; IPNP = 0
          HP = 0. ; ANGP = 0.
          IX0 = 0
          IY0 = 0
          RETURN
C          *************  WHERE  *************
C          ***********              **********
          ENTRY WHERE(XAV,YAV,FACT)
          KP3 = IESC+ID*IC2+70*IC3 ; KP4 = IESC+ID*IC2+76*IC3
          KP5 = IESC+ID*IC2+75*IC3 ; KP6 = IESC+ID*IC2+69*IC3
          PRINT 120,KP3
          PRINT,"WHEN PROMPT LIGHT COMES ON POSITION PEN,",
         &" PRESS CALL BUTTON AND RELEASE"
          PRINT 120,KP6
          PRINT 120,KP5
          READ FMT,IN1,IN2,IN3,IN4,IN5,IN6,IN7
          PRINT 120,KP4
          IN1 = IN1/IC1-32 ; IN2 = IN2/IC1-32
          IN3 = IN3/IC1-32 ; IN4 = IN4/IC1-32
          IN5 = (IN5/IC1-32)/8 ; IN6 = (IN6/IC1-32)/8
          XAV = IN1*C1+IN3*C2+IN5*C3 ; YAV = IN2*C1+IN4*C2+IN6*C3
          RETURN
C          *************  PLOT  *************
C          ***********             **********
          ENTRY PLOT(X,Y,IPN)
          IPNX = IPN
          IX = X*273+IX0
          IY = Y*273+IY0
          IF(IPNX) 10,99,20
       10 IPNX = -IPNX
          IX0 = X*273
```

```
      IYO = Y*273
      IX = IXO
      IY = IYO
   20 IF(IPNX-3) 40,30,90
   30 IF(KP(IK-1).EQ.IGS) GO TO 40
      KP(IK) = IGS
      IC = IC+29 ; IK = IK+1
   40 IF(IX.LT.0.OR.IY.LT.0.OR.IX.GT.4095.OR.IY.GT.2730) GO TO 95
      HIX = IX/IC4
      IX = IX-HIX*IC4
      HIX = HIX+32
      LOX = IX/IC5
      IXLO = IX-LOX*IC5
      LOX = LOX+64
      HIY = IY/IC4
      IY = IY-HIY*IC4
      HIY = HIY+32
      LOY = IY/IC5
      XLOY = 4*(IY-LOY*IC5)+IXLO+96
      LOY = LOY+96
      L1 = .F. ; L3 = .F.
      IF(IPNP.NE.IPN) L3 = .T.
      IPNP = IPN ; IS = 2
      IF(IK-147) 50,50,85
   50 IF(HIY-HIYP) 51,52,51
   51 KP(IK) = HIY*IC1
      IC = IC+HIY
      IK = IK+1
      HIYP = HIY
      L3 = .T.
   52 IF(XLOY-XLOYP) 54,58,54
   54 KP(IK) = XLOY*IC1
      IC = IC+XLOY
      IK = IK+1
      XLOYP = XLOY
      KP(IK) = LOY*IC1
      IC = IC+LOY
      IK = IK+1
      LOYP = LOY
      L1 = .T. ; L3 = .T.
   58 IF(LOY-LOYP) 60,62,60
   60 KP(IK) = LOY*IC1
      IC = IC+LOY
      IK = IK+1
      LOYP = LOY
      L1 = .T. ; L3 = .T.
   62 IF(HIX-HIXP) 64,70,64
   64 IF(L1) GO TO 66
      KP(IK) = LOY*IC1
      IC = IC+LOY
      IK = IK+1
      L3 = .T.
   66 KP(IK) = HIX*IC1
      IC = IC+HIX
      IK = IK+1
```

```
      MIXP = MIX
   70 IF(L3) GO TO 71
      IF(LOX-LOXP) 71,72,71
   71 KP(IK) = LOX+IC1
      IC = IC+LOX
      IK = IK+1
      LOXP = LOX
   72 GO TO (99,210,360) ,L2
   85 IC = MOD(IC,4095)
      IF(IC.EQ.0) IC = 4095
      ICL = ALOG10(IC)
      ICC = 0
      KP(IK) = IESC
      KP(IK+1) = KP(2)
      KP(IK+2) = IRPR
      IK = IK+2
      ENCODE (FMT,100) IK,ICL+1
   88 PRINT FMT,(KP(I),I=1,IK),IC
      READ FMT,ICK
      IF(ICK/IC1.EQ.73) GO TO 97
      IC = IC1
      IK = 4
      GO TO (50,93,72,220,270,91) ,IS-1
   90 IS = 7
      IF(IPNX.EQ.4) GO TO 92
      IF(IK-146) 91,91,85
   91 KP(IK) = IGS
      KP(IK+1) = 53+IC1
      KP(IK+2) = 107+IC1
      KP(IK+3) = 106+IC1
      KP(IK+4) = 63+IC1
      KP(IK+5) = 95+IC1
      IK = IK+6 ; IC = IC+453
   92 IS = 3
      GO TO 85
   93 PRINT 120,KP2,KP1
      RETURN
   95 IF(KP(IK-1).EQ.IGS) GO TO 72
      KP(IK) = IGS
      IK = IK+1 ; IC = IC+29
      IS = 4
      IF(IK-152) 72,72,85
   97 ICC = ICC+1
      IF(ICC-5) 88,98,98
   98 PRINT 120,KP2,KP1
      PRINT," PLOTTER OR PROGRAM ERROR"
      STOP "ERROR"
   99 RETURN
  100 FORMAT(T2,I3,T9,I1)
  120 FORMAT(2A4,A3,I3,A3)
C          ************ SYMBOL ************
C          ***********           **********
      ENTRY SYMBOL(X,Y,H,IBCD,ANG,NC)
      IF(NC) 320,200,200
  200 IF(X-999.) 205,240,205
```

```
 205 IX = X*273+IX0
     IY = Y*273+IY0
     L2 = 2
     GO TO 30
 210 L2 = 1
     IS = 5
     IF(IK-123) 220,220,85
 220 IF(H-HP) 222,230,222
 222 CONTINUE
     HP = H
     KP(IK) = IESC
     KP(IK+1) = KP(2)
     KP(IK+2) = 73*IC1
     IC = IC+ID+144
     IK = IK+3
     YVAL = H*HYF
     XVAL = YVAL*HXF
     ENCODE(IASC,130) IFIX(XVAL+.5)
 130 FORMAT(I4)
     IST = -1
 224 L = 0
     DO 226 I = 1,4
     IAC = FLD(L,9,IASC)
     IF(IAC.LT.48) GO TO 226
     KP(IK) = IAC*IC1
     IK = IK+1
     IC = IC+IAC
 226 L = L+9
     IF(IST) 228,230,240
 228 IST = 0
     KP(IK) = 44*IC1
     IK = IK+1
     ENCODE(IASC,130) IFIX(YVAL+.5)
     GO TO 224
 230 IF(ANG-ANGP) 232,240,232
 232 ANGP = ANG
     IST = 1
     KP(IK) = IESC
     KP(IK+1) = KP(2)
     KP(IK+2) = 74*IC1
     IK = IK+3
     IC = IC+ID+101
     ENCODE(IASC,130) IFIX(ANG+.5)
     GO TO 224
 240 CONTINUE
     KP(IK) = 4160749568
     IK = IK+1
     IC = IC+31
     IF(NC) 260,250,260
 250 CONTINUE
     CALL BCDASC(IBCD,IASB,6)
     IAC = FLD(9,9,IASB(2))
     KP(IK) = IAC*IC1
     IC = IC+IAC
     IK = IK+1
```

```
      GO TO 290
  260 CONTINUE
      NT = NC/4
      NL = NC-NT*4
      IF(NL.GT.0) NT = NT+1
      IF(NL.LE.0) NL = 4
      IAC = FLD(0,9,IBCD(1))
      IF(IAC.GT.127) GO TO 300
      IS = 6
      DO 270 M =1,NT
      L = 0
      IF(M.LT.NT) JT = 4
      IF(M.GE.NT) JT = NL
      DO 270 J = 1,JT
      IAC = FLD(L,9,IBCD(M))
      KP(IK) = IAC*IC1
      IK = IK+1
      IC = IC+IAC
      IF(IK-151) 270,270,85
  270 L = L+9
  290 KP(IK) = IGS
      IK = IK+1
      IC = IC+29
      RETURN
  300 IF(NC.GT.7) GO TO 290
      CALL BCDASC(IBCD,IASB,NC)
      DO 310 M =1,NT
      L = 0
      IF(M.LT.NT) JT = 4
      IF(M.GE.NT) JT = NL
      DO 310 J = 1,JT
      IAC = FLD(L,9,IASB(M))
      KP(IK) = IAC*IC1
      IK = IK+1
      IC = IC+IAC
  310 L = L+9
      GO TO 290
        ************ SPECIAL SYMBOLS ***********
        *********                       ********
  320 CONTINUE
      DATA ITAB /
        PLOT SYMBOLS
          0 1
     & 133266,4860164,6,0,6428818,3158088,4860124,6,
          2 3
     & 1050770,25762,0,0,4225170,4727252,6,0,
          4 5
     & 1079570,4719072,6,0,592018,1648788,0,0,
          6 7
     & 5310610,4727266,6,0,1181970,1646599,0,0,
          8 9
     & -8358702,1851426,25745,0,555282,4850130,6,0,
          10 11
     & 6666514,38496,2900661,1648923,-6357742,4276676,1982471,25730,
          12 13
```

```
C
     & 149522,25732,0,0,555154,402,0,0,
C        14 (GAMMA)
     & 4599036,5025929,1805410,0,
C        15 SIGMA
     & 8592565,4989008,435,0/
       DATA INEG /-8388608/
       RAD = ANG*.01745329
       CTH = COS(RAD)
       STH = SIN(RAD)
       L2 = 3
       FM = 68.25*H
       XI = X*273+IX0
       YI = Y*273+IY0
       IP = 3
       IF(NC.LT.-1) IP = 2
       IF(IP.EQ.3) IPNP = -IPNP
       MC = IBCD(1)+1
       IF(MC.LT.1.OR.MC.GT.16) GO TO 390
       IF(MC.GT.14) FM = 39*H
       ISP = 2
       IF(MC.GT.14) ISP = 0
       DO 350 IA =1,4
       IT = ITAB(IA,MC)
       IF = 0
       IF(IT) 330,340,340
   330 IT = IT-INEG
       IF = 1
   340 DO 350 IB =1,8
       IO = (IA-1)*8+IB
       IOUT(IO) = IT-IT/8*8
       IT = IT/8
       IF(IB.EQ.8.AND.IF.EQ.1) IOUT(IO) = IOUT(IO)+4
   350 CONTINUE
       K = 1
   370 CONTINUE
       IF(IOUT(K)-7) 354,352,354
   352 IP = 3
       GO TO 380
   354 IF(IOUT(K)-6) 356,390,356
   356 DX = (IOUT(K)-ISP)
       DY = (IOUT(K+1)-ISP)
       IX = (DX*CTH-DY*STH)*FM+XI
       IY = (DX*STH+DY*CTH)*FM+YI
       GO TO (40,40,30) ,IP
   360 IP = 2
   380 K = K+2
       IF(K-31) 370,370,390
   390 L2 = 1
       GO TO 290
       END
C


C        ************ NUMBER ***********
C        **********           *********
       SUBROUTINE NUMBER(X,Y,H,FPN,ANG,ND)
       CHARACTER FMTN *7,IBCN *50
```

```
      FPNX = FPN
      NDI = 1
      IF(FPNX) 10,30,20
   10 FPNX = -FPNX
      NDI = 2
   20 IF(FPNX.LT.10) GO TO 30
      NDI = NDI + IFIX(ALOG10(FPNX))
   30 IF(ND) 50,40,40
   40 NDT = NDI+ND+1
      ENCODE (FMTN,110) NDT,ND
      ENCODE (IBCN,FMTN) FPN
      NC = NDT
      GO TO 80
   50 FPNX = FPN
      NDX = ND+1
      IF(NDX) 60,70,70
   60 FPNX = FPNX*10.**NDX
      NDI = MAX(NDI+NDX,1)
   70 ENCODE (FMTN,120) NDI
      ENCODE (IBCN,FMTN) IFIX(SIGN(ABS(FPNX)+.5,FPNX))
      NC = NDI
   80 CALL SYMBOL(X,Y,H,IBCN,ANG,NC)
      RETURN
  110 FORMAT(2H(F,I2,1H.,I1,1H))
  120 FORMAT(2H(I,I2,1H))
      END
C


**************************** PLOT2 ******************************
      SUBROUTINE PLOT2(X,Y,N)
      DIMENSION X(1),Y(1)
      CHARACTER *70 LBX,LBY,LBX2,LBY2,LABT*1(70),
     &          FMT*6/6H(70A1)/,FIN*3/3H(V)/
      LOGICAL L1/.T./
      DATA IN /5/
      IF(L1) PRINT,"READ X0,Y0,SFX,SFY,IA,IDASH,THETA"
      READ(IN,FIN) X0,Y0,SFX,SFY,IA,IDASH,THETA
      IF(SFX) ,99,
      SPX = 1. ; SPY = 1.
      IF(IA.EQ.1) GO TO 29
      LX = -1 ; LY = 1 ; LX2 = 1 ; LY2 = -1
      XL2 = 0. ; YL2 = 0. ; ITX = 1 ; ITY = 1
      IF(L1) PRINT,"READ HTX,XL,XS,NDX,NPX,SPX,ITX"
      READ(IN,FIN) HTX,XL,XS,NDX,NPX,SPX,ITX
      IF(L1) PRINT,"READ HTY,YL,YS,NDY,NPY,SPY,ITY"
      READ(IN,FIN) HTY,YL,YS,NDY,NPY,SPY,ITY
      IF(SPX.LE.0.) SPX = 1. ; IF(SPY.LE.0.) SPY = 1.
      IF(ITX.EQ.0) ITX = 1 ; IF(ITY.EQ.0) ITY = 1
      IF(HTX.LE.0.) GO TO 7
      IK = 1
      IF(L1) PRINT,"READ X-LABEL"
    1 READ(IN,FMT) LABT
      DO 2 I=1,70
      K = 71-I
      IF(LABT(K).NE.1H ) GO TO 3
    2 CONTINUE
```

```
    5 GO TO (6,8,26,28) ,IK
    6 ENCODE(LBX,FMT) (LABT(I),I=1,K)
      LX = -K
    7 IF(HTY.LE.0.) GO TO 9
      IK = 2
      IF(L1) PRINT,"READ Y-LABEL"
      GO TO 1
    8 ENCODE(LBY,FMT) (LABT(I),I=1,K)
      LY = K
    9 IF(IA.NE.2) GO TO 29
      IF(L1) PRINT,"READ HTX2,XL2,XS2,NDX2,NPX2,XY0"
      READ(IN,FIN) HTX2,XL2,XS2,NDX2,NPX2,XY0
      IF(L1) PRINT,"READ HTY2,YL2,YS2,NDY2,NPY2,YX0"
      READ(IN,FIN) HTY2,YL2,YS2,NDY2,NPY2,YX0
      IF(HTX2.LE.0.) GO TO 27
      IK = 3
      IF(L1) PRINT,"READ X-LABEL2"
      GO TO 1
   26 ENCODE(LBX2,FMT) (LABT(I),I=1,K)
      LX2 = K
   27 IF(HTY2.LE.0.) GO TO 29
      IK = 4
      IF(L1) PRINT,"READ Y-LABEL2"
      GO TO 1
   28 ENCODE(LBY2,FMT) (LABT(I),I=1,K)
      LY2 = -K
   29 IF(IDASH.NE.0) GO TO 12
      TH = THETA*.0174532925
      S = SIN(TH) ; C = COS(TH)
      XCF = SPX*C/SFX ; XSF = SPX*S/SFX
      YSF = SPY*S/SFY ; YCF = SPY*C/SFY
      CALL PLOTS("A")
      CALL PLOT(X0,Y0,-3)
      DO 10 I = 1,N
      H = X(I)*XCF - Y(I)*YSF
      V = X(I)*XSF + Y(I)*YCF
      IF(I.EQ.1) CALL PLOT(H,V,3)
   10 CALL PLOT(H,V,2)
      GO TO 14
   12 IF(L1) PRINT,"DASHED LINE - SL1,SL2 = SOLID LENGTHS,",
     &        " BL = BLANK LENGTH (INCHES)"
      IF(L1) PRINT,"READ SL1,SL2,BL"
      READ(IN,FIN) SL1,SL2,BL
      CALL PLOTS("A")
      CALL PLOT(X0,Y0,-3)
      CALL DASHED(X,Y,N,SFX/SPX,SFY/SPY,SL1,SL2,BL,THETA)
   14 IF(IA-1) ,98,
      XS = XS*SPX ; YS = YS*SPY
      IF(XL.LE.0.) GO TO 16
      XL = XL*SPX ; XST = XS*SFX/SPX
      CALL AXIS14(XS,YS,LBX,LX,HTX,XL,NDX,0,XST,SFX,SPX,
     &                ITX,NPX,THETA)
   16 IF(YL.LE.0.) GO TO 17
      YL = YL*SPY ; YST = YS*SFY/SPY
      CALL AXIS14(XS,YS,LBY,LY,HTY,YL,NDY,1,YST,SFY,SPY,
```

```
      &             ITY,NPY,THETA)
   17 IF(XL2.LE.0.) GO TO 18
      XL2 = XL2*SPX ; XS2 = XS2*SPX ; XY0 = XY0*SPY
      XST2 = XS2*SFX/SPX
      CALL AXIS14(XS2,XY0,LBX2,LX2,HTX2,XL2,NDX2,0,XST2,SFX,SPX,
      &             ITX,NPX2,THETA)
   18 IF(YL2.LE.0.) GO TO 98
      YL2 = YL2*SPY ; YS2 = YS2*SPY ; YX0 = YX0*SPX
      YST2 = YS2*SFY/SPY
      CALL AXIS14(YX0,YS2,LBY2,LY2,HTY2,YL2,NDY2,1,YST2,SFY,SPY,
      &             ITY,NPY2,THETA)
   98 CALL PLOT(0.,0.,999)
   99 RETURN
      ENTRY INFIL(INF)
      IN = INF ; L1 = .F.
      RETURN
      END
C



C      REM ****** "INITIATE DATA PLOT" SUBROUTINE ******
      SUBROUTINE DASHED(X8,Y8,M,SFX,SFY,SL1,SL2,BL,THETA)
      DIMENSION X8(1),Y8(1)
      INTEGER F,F2,D3
      REAL N1(2),N2,N5,N6,L1,L2
      LOGICAL L3
      COMMON /BASIC/ F,F2,H0,H5,L1,L2,N1,N2,N6,G0,G1,
     &                  R0,R1,S3,S4,U1,U2,V0,V5,J0,D3,L3
      TH = THETA*.0174532925
      S = SIN(TH) ; C = COS(TH)
      XCF = C/SFX ; XSF = S/SFX
      YSF = S/SFY ; YCF = C/SFY
      N1(1) = SL1
      N1(2) = SL2
      N2 = BL
      F=1
      F2=0
      L3 = .F.
      J0 = 2
      D3 = -1
      U1 = X8(1)*XCF - Y8(1)*YSF
      R1 = X8(1)*XSF + Y8(1)*YCF
      CALL PLOT(U1,R1,3)
      DO 100 I=2,M
      U0 = U1
      H5 = U0
      R0 = R1
      V5 = R0
      U1 = X8(I)*XCF - Y8(I)*YSF
      R1 = X8(I)*XSF + Y8(I)*YCF
      D1=(U1-U0)
      D2=(R1-R0)
      D0=SQRT(D1**2+D2**2)
      IF(D0) ,100,
      U1=D1/D0
      U2=D2/D0
      IF(F2.EQ.0) GO TO 10
```

```
      L1=U1*N6
      L2=U2*N6
      H0=H5
      V0=V5
      CALL ENTRY1
      IF(F2.EQ.1) GO TO 100
   10 CALL SUBLIN
      IF(F2.NE.1) GO TO 10
  100 CONTINUE
      RETURN
      END
C


C      REM ****** "PLOT DASHED-LINE" SUBROUTINE ******
      SUBROUTINE SUBLIN
      INTEGER F,F2,D3
      REAL N1(2),N2,N5,N6,L1,L2
      LOGICAL L3
      COMMON /BASIC/ F,F2,H0,H5,L1,L2,N1,N2,N6,Q0,Q1,
     &               R0,R1,S3,S4,U1,U2,V0,V5,J0,D3,L3
      H0=H5
      V0=V5
      IF(F.EQ.2) GO TO 20
      J0 = J0+D3
      L1=U1*N1(J0)
      L2=U2*N1(J0)
      D3 = -D3
      GO TO 30
   20 L1=U1*N2
      L2=U2*N2
      ENTRY ENTRY1
   30 H5=H5+L1
      V5=V5+L2
      IF(ABS(H5-Q0).GT.ABS(Q1-Q0)) GO TO 70
      IF(ABS(V5-R0).GT.ABS(R1-R0)) GO TO 70
      F2=0
      IF(F.EQ.1) GO TO 50
      F=1
   40 H5L = H5
      V5L = V5
      L3 = .T.
      RETURN
   50 F=2
   60 IF(.NOT.L3) GO TO 65
      CALL PLOT(H5L,V5L,3)
      L3 = .F.
   65 CALL PLOT(H5,V5,2)
      RETURN
   70 H5=Q1
      V5=R1
      L1=H5-H0
      L2=V5-V0
      N5=SQRT(L1**2+L2**2)
      IF(F2.EQ.0) GO TO 80
      N6=N6-N5
      GO TO 110
```

```
   80 IF(F.EQ.2) GO TO 100
      N6=N1(J0)-N5
      GO TO 110
  100 N6=N2-N5
  110 F2=1
      IF(F-1) 60,60,40
      END
C


      SUBROUTINE AXIS14(X, Y, IBCD, NC, H, SIZE, NN, IXY, XMIN, DX,
     &SPACE, ITIC, NP10, THETA )
      DIMENSION LBL(2),IBCD(1)
      DATA IBCD1/4H    /,LBL/4H(X10,4H  ) /
      XY = IXY
      ANGLE = XY*90.+THETA
      TH = THETA*.01745329
      S = SIN(TH)
      C = COS(TH)
      TIC = SIGN(1,ITIC)
      SPAC = SPACE
      G = H
      P10 = NP10
      X2 = X
      Y2 = Y
      XT = 0.
      YT = 0.
      LINE = 2
      SIZ = SIZE
      IF ( SIZ) 1,16,100
    1 LINE = 3
      SIZ = -SIZ
  100 ND = NN
      NA = NN
      IF (ND) 3,2,2
    2 NDIG = ND + 1
      GO TO 30
    3 ND = 0
      NDIG = 0
   30 NSPACE = SIZ / SPAC + .5
      FNSPAC = NSPACE
      TL = FNSPAC * SPAC
      HO2 = G * .5
      HO7 = HO2 / 3.5
      HO7T24 = 4. * G
      POWER = 10. ** (-NP10)
      DELX = POWER * DX
      XMEN = POWER * XMIN
      ANG = 1.-XY
      NB = NC
      ALAB = 1.
      XYL = .18
      IF (NB) 5, 6, 6
    5 NB = -NB
      ALAB = -1.
      XYL = XYL+G
    6 TICXY = (2.*XY-1.)*ALAB*TIC*.1
```

```
      XTIC = TICXY * XY
      YTIC = TICXY * ANG
      AK = NB
      IF ( P10) 60,65,60
   60 AK = AK + 8.
   65 STITLE = TL * .5 - (7.*AK - 3.) * HO7 * .5
      TICM1 = .16 - TIC * .05
      ANOMIN = 24.
      XNUMB = XMEN
      LIN = 3
      NMAX = 0
      J = 0
      DO 12 I=J,NSPACE
      NDIGIT = NDIG
      CALL PLOT (X2, Y2,  LIN )
      LIN = LINE
      X1 = XT+XTIC
      Y1 = YT+YTIC
      XP = X1*C - Y1*S + X
      YP = X1*S + Y1*C + Y
      CALL PLOT (XP, YP, 2 )
      IF (G) 7, 11, 7
    7 IF(MOD(I,ITIC)) 8,8,20
    8 ITEMP = .434294482 *ALOG(ABS(XNUMB)+.5 * 10.**(-ND))+1.
      IF(ITEMP)70,70,71
   70 ITEMP = 1
   71 NDIGIT = NDIGIT+ITEMP
      IF(XNUMB)9,10,10
    9 NDIGIT = NDIGIT + 1
   10 IF(NDIGIT - NMAX)77,77,76
   76 NMAX = NDIGIT
   77 FDIGIT = NDIGIT
      CENTER = (7. * FDIGIT - 3.) * HO7 * .5
      XANO = - ALAB *  XY * ( TICM1 + CENTER )  - CENTER
      YANO = ALAB *  ANG * ( TICM1 + HO2) - HO2
      X1 = XANO + XT
      Y1 = YANO + YT
      XP = X1*C - Y1*S + X
      YP = X1*S + Y1*C + Y
      CALL NUMBER (XP, YP, G , XNUMB, THETA, NA )
   20 XNUMB = XNUMB + DELX
      IF(ANOMIN-XANO)11,11,78
   78 ANOMIN = XANO
   11 CALL PLOT(X2, Y2, 3 )
      XT = XT + SPAC  *  ANG
      YT = YT + SPAC  *  XY
      X2 = XT*C - YT*S + X
      Y2 = XT*S + YT*C + Y
   12 CONTINUE
      IF (G) 13, 16, 13
   13 NX = NB/4
      IF(AMOD(NB,4))18,18,17
   17 NX = NX + 1
   18 DO 15 I=1,NX
      IF(IBCD(I)-IBCD1)19,15,19
```

```
   15 CONTINUE
      GO TO 16
   19 FNMAX = NMAX
      ANGWID = (7. * FNMAX - 3.) * H07 * .5
      XTITLE = XY * (ANGMIN + ANGWID - ALAB *(ANGWID + XYL)) +
     & ANG * STITLE
      YTITLE = ANG * (YANG + ALAB * (G + .18 )) +  XY * STITLE
      XP = XTITLE*C - YTITLE*S + X
      YP = XTITLE*S + YTITLE*C + Y
      CALL SYMBOL(XP, YP, G, IBCD, ANGLE, NB )
      IF (P10) 14, 16, 14
   14 FNB = NB
      BN = (FNB + 1.) *  G
      XTITLE = XTITLE +  ANG * BN
      YTITLE = YTITLE +  XY * BN
      XP = XTITLE*C - YTITLE*S + X
      YP = XTITLE*S + YTITLE*C + Y
      CALL SYMBOL (XP,YP,G,LBL,ANGLE,7)
      XTITLE = XTITLE  +  ANG * H07T24 -XY*H02
      YTITLE = YTITLE  +  XY  * H07T24 +ANG*H02
      XP = XTITLE*C - YTITLE*S + X
      YP = XTITLE*S + YTITLE*C + Y
      CALL NUMBER ( XP, YP, 5.* H07, P10, ANGLE, -1 )
   16 RETURN
      END
```

```
      SUBROUTINE LOGAXS(X,Y,BCD,NC,H,SIZE,NCYL,IXY,XMIN,NA,ITIC)
      Z = Y
      G = H
      KCYL = NCYL
      KXY = IXY
      KA = NA
      KTIC = ITIC
      ILAB = 1
      XYL = .18
      IF(NC)1,2,2
    1 ILAB = -1
      XYL = XYL+G
    2 TL = SIZE*KCYL
      NANG = 1-KXY
      NB1 = NC*ILAB
      LANG = (2*KXY-1)*ILAB*KTIC
      TICXY = LANG*0.1
      XTIC = TICXY*KXY
      YTIC = TICXY*NANG
      ITICM1 = 1-KTIC
      H02 = G/2.
      H07 = G/7.
      FIVH07 = H07*5.
      FH0702 = .5*FIVH07
      STITLE = .5*TL - .5*H07*(7*NB1-3)
      XT = X
      YT = Z
      CL = SIZE
      ANG = 90.0*KXY
      ANO = .16-KTIC*.05
      ANO1 = ANO+FH0702
      P10 = ALOG10(XMIN)
      P10M = P10+KCYL
      XPN = .5*G
      IF(P10.LT.0.0.OR.P10M.GT.9.) XPN = XPN+FH0702
      CENTER = 5.5*H07+XPN*KXY+NANG*H02
      XANO = -ILAB*KXY*(ANO+CENTER) - CENTER
      YANO = ILAB*NANG*(ANO1+H02) - H02
      IF(KA)12,12,10
   10 XANOP = XANO+2.2*G
      YANOP = YANO+.7*G
      CALL SYMBOL(XT+XANO,YT+YANO,G,2H10,0.0,2)
      CALL NUMBER(XT+XANOP,YT+YANOP,FIVH07,P10,0.0,-1)
   12 CALL PLOT(XT+XTIC,YT+YTIC,3)
      CALL PLOT(XT,YT,2)
      DO 60 N=1,KCYL
      TL = CL*(N-1)
      TL02 = TL*KXY
      TL = TL*NANG
      DO 50 I=2,10
      FLPCOI = I
      TLINC = ALOG10(FLPCOI) * CL
      XI = TLINC*NANG
      XP = XI+XT+TL
      YI = TLINC*KXY
```

```
      YP = YI+YT+TLO2
      CALL PLOT(XP,YP,2)
      CALL PLOT(XP+XTIC,YP+YTIC,2)
   30 CALL PLOT(XP,YP,3)
      IF(KA) 60,60,50
   50 CONTINUE
      CALL SYMBOL(XP+XANO,YP+YANO,G,2H10,0.0,2)
      P10 = P10+1
      CALL NUMBER(XP+XANOP,YP+YANOP,FIVH07,P10,0.0,-1)
      CALL PLOT(XP,YP,3)
   60 CONTINUE
      IF(G) 80,80,70
   70 XTITLE = KXY*(XANO+CENTER-ILAB*(CENTER+XYL)) + NANG*STITLE
      YTITLE = NANG*(YANO+ILAB*(G+.18)) + KXY*STITLE
      CALL SYMBOL(XTITLE+XT,YTITLE+YT,G,BCD,ANG,NB1)
   80 RETURN
      END
C
```

Instructions for PLOTLL

All input is in free-field format, and the program will call for the variables by name. The plot specification input variables are indicated in Figure B2.

Input No. 1: XØ, YØ, XMIN, XCL, YMIN, YCL, IA, IDASH

XØ,YØ--X and Y coordinates of the origin on the paper, in inches from the lower left of plotting surface

XMIN--starting value for X-axis in user units (lowest decade value, i.e., 0.1, 1, 10, 100, etc.)

XCL--number of inches per log-cycle on X-axis

YMIN--starting value for Y-axis in user units (0.1, 1, 10, 100, etc.)

YCL--number of inches per log cycle on Y-axis

IA--axes specification

0--plot axes
1--no axes
2--X and Y axes drawn plus lines to form right and top border

IDASH--=0, plots solid line
≠0, plots dashed line

Input No. 2: HTX, NXC, NAX

HTX--height of characters in inches for X-axis label

NXC--number of X-cycles

NAX--=1

Input No. 3: HTY, NYC, NAY

Exactly analogous to Input No. 2 except for Y-axis

Input No. 4: X-LABEL

Input No. 5: Y-LABEL

Input No. 6: SL1, SL2, BL

Input only if IDASH ≠ 0

SL1,SL2,BL--length of dashes and blank in inches

If IA = 2, the following two input specify labeling of of the right and upper axes.

Input No. 7: HTX2, NXC2, NAX2, XYO

Input No. 8: HTY2, NYC2, NAY2, YXO

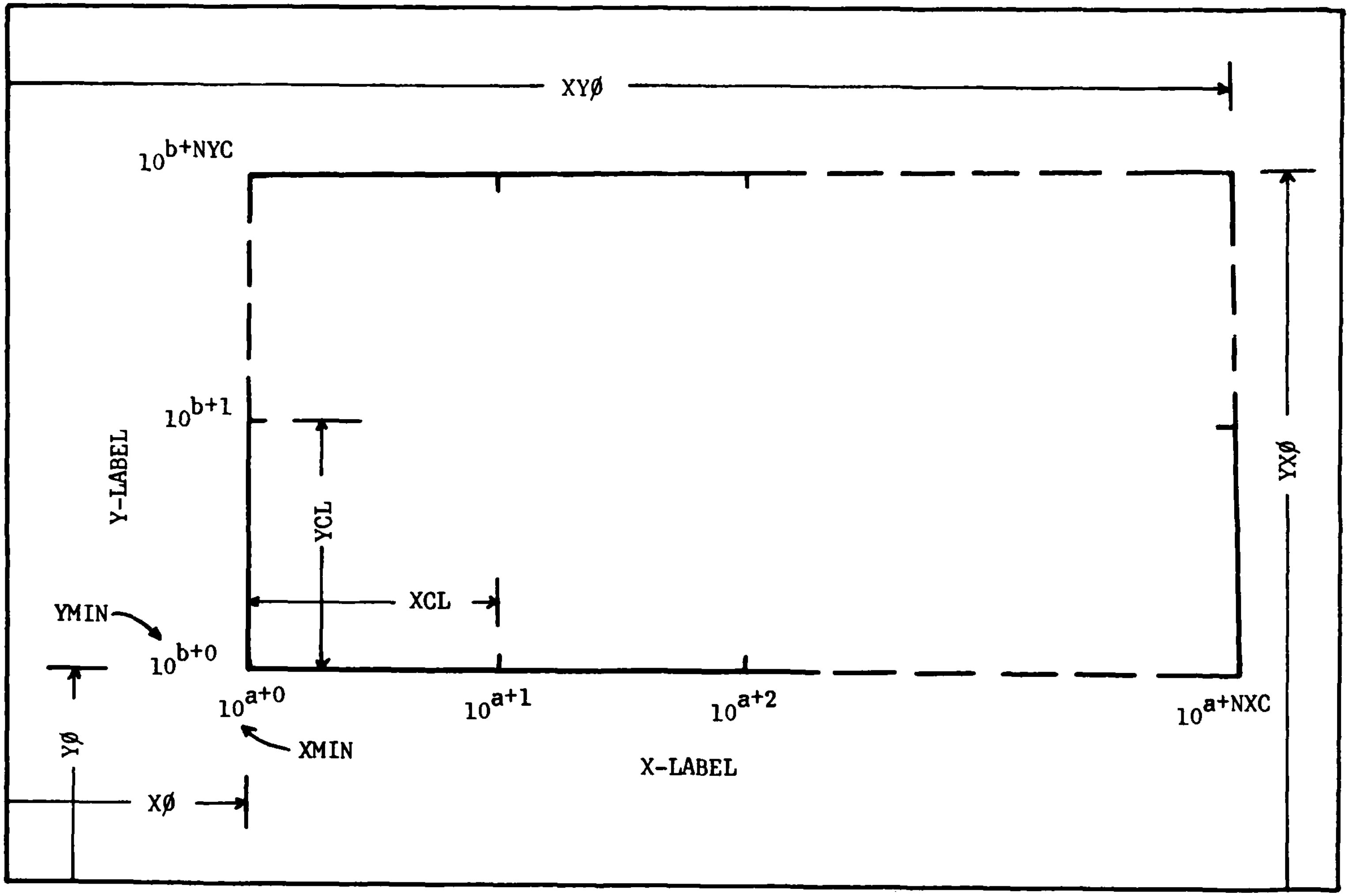

Figure B2. Definition of plot specification input parameters for PLOTLL. XØ, YØ, XCL, YCL, XYØ, YXØ are in inches. XMIN and YMIN are in user units and expressed in decimal form (i.e., .01, .1, 1, 10, 100, etc.)

HYX2,HTY2--height of characters in inches

NXC2,NYC2--number of X- and Y-cycles, respectively.

NAX2,NAY2--set both = -1

XYO,YXO--coordinates in inches of the upper right corner
of plot

```
**************************** PLOTLL ********************************
      SUBROUTINE PLOTLL(X,Y,N)
      COMMON /FLINP/ L1,IN
      DIMENSION X(1),Y(1)
      CHARACTER *60 LBX,LBY,LBX2,LBY2,LABT*1(60),
    &          FMT*6/6H(60A1)/,FIN*3/3H(V)/
      LOGICAL L1
      DATA L1/.T./ , IN/5/
      IF(L1) PRINT,"READ X0,Y0,XMIN,XCL,YMIN,YCL,IA,IDASH"
      READ(IN,FIN) X0,Y0,XMIN,XCL,YMIN,YCL,IA,IDASH
      IF(XCL) ,99,
      IF(IA.EQ.1) GO TO 29
      LX = -1 ; LY = 1 ; LX2 = 1 ; LY2 = -1
      XL2 = 0. ; YL2 = 0. ; NXC2 = 0 ; NYC2 = 0
      IF(L1) PRINT,"READ HTX,NXC,NAX"
      READ(IN,FIN) HTX,NXC,NAX
      IF(L1) PRINT,"READ HTY,NYC,NAY"
      READ(IN,FIN) HTY,NYC,NAY
      IF(HTX.LE.0.) GO TO 7
      IK = 1
      IF(L1) PRINT,"READ X-LABEL"
    1 READ(IN,FMT) LABT
      DO 2 I=1,60
      K = 61-I
      IF(LABT(K).NE.1H ) GO TO 3
    2 CONTINUE
    3 GO TO (6,8,26,28) ,IK
    6 ENCODE(LBX,FMT) (LABT(I),I=1,K)
      LX = -K
    7 IF(HTY.LE.0.) GO TO 9
      IK = 2
      IF(L1) PRINT,"READ Y-LABEL"
      GO TO 1
    8 ENCODE(LBY,FMT) (LABT(I),I=1,K)
      LY = K
    9 IF(IA.NE.2) GO TO 29
      IF(L1) PRINT,"READ HTX2,NXC2,NAX2,XY0"
```

```
      READ(IN,FIN) MTX2,NXC2,NAX2,XYO
      IF(L1) PRINT,"READ MTY2,NYC2,NAY2,YXO"
      READ(IN,FIN) MTY2,NYC2,NAY2,YXO
      IF(XYO.LE.0.) XYO = NYC2*YCL
      IF(YXO.LE.0.) YXO = NXC2*XCL
      IF(MTX2.LE.0.) GO TO 27
      IK = 3
      IF(L1) PRINT,"READ X-LABEL2"
      GO TO 1
   26 ENCODE(LBX2,FMT) (LABT(I),I=1,K)
      LX2 = K
   27 IF(MTY2.LE.0.) GO TO 29
      IK = 4
      IF(L1) PRINT,"READ Y-LABEL2"
      GO TO 1
   28 ENCODE(LBY2,FMT) (LABT(I),I=1,K)
      LY2 = -K
   29 XO = ALOG(XMIN)
      YO = ALOG(YMIN)
      XLF = .434294482*XCL
      YLF = .434294482*YCL
      IF(IDASH.NE.0) GO TO 12
      CALL PLOTS("A")
      CALL PLOT(XO,YO,-3)
      DO 10 I = 1,N
      IF(X(I).LE.0.) X(I) = XMIN
      IF(Y(I).LE.0.) Y(I) = YMIN
      H = (ALOG(X(I))-XO)*XLF
      V = (ALOG(Y(I))-YO)*YLF
      IF(I.EQ.1) CALL PLOT(H,V,3)
   10 CALL PLOT(H,V,2)
      GO TO 14
   12 IF(L1) PRINT,"DASHED LINE - SL1,SL2 = SOLID LENGTHS,",
     &        " BL = BLANK LENGTH (INCHES)"
      IF(L1) PRINT,"READ SL1,SL2,BL"
      READ(IN,FIN) SL1,SL2,BL
      CALL PLOTS("A")
      CALL PLOT(XO,YO,-3)
      DO 13 I=1,N
      IF(X(I).LE.0.) X(I) = XMIN
      IF(Y(I).LE.0.) Y(I) = YMIN
      X(I) = (ALOG(X(I))-XO)*XLF
      Y(I) = (ALOG(Y(I))-YO)*YLF
   13 CONTINUE
      CALL DASHED(X,Y,N,1.,1.,SL1,SL2,BL,0.)
   14 IF(IA-1) ,98,
      IF(NXC.LE.0) GO TO 16
      CALL LOGAXS(0.,0.,LBX,LX,MTX,XCL,NXC,0,XMIN,NAX,1)
   16 IF(NYC.LE.0) GO TO 17
      CALL LOGAXS(0.,0.,LBY,LY,MTY,YCL,NYC,1,YMIN,NAY,1)
   17 IF(NXC2.LE.0) GO TO 18
      CALL LOGAXS(0.,XYO,LBX2,LX2,MTX2,XCL,NXC2,0,XMIN,NAX2,1)
   18 IF(NYC2.LE.0) GO TO 98
      CALL LOGAXS(YXO,0.,LBY2,LY2,MTY2,YCL,NYC2,1,YMIN,NAY2,1)
   98 CALL PLOT(0.,0.,999)
```



```
   99 RETURN
      END
C
```

```
***************************** PLOTLY ********************************
      SUBROUTINE PLOTLY(X,Y,N)
      COMMON /FLINP/ L1,IN
      DIMENSION X(1),Y(1)
      CHARACTER *60 LBX,LBY,LBX2,LBY2,LABT*1(60),
     &          FMT*6/6H(60A1)/,FIN*3/3H(V)/
      LOGICAL L1
      DATA L1/.T./ , IN/5/
      IF(L1) PRINT,"READ X0,Y0,SFX,YMIN,YCL,IA,IDASH"
      READ(IN,FIN) X0,Y0,SFX,YMIN,YCL,IA,IDASH
      IF(SFX) ,99,
      SPX = 1.
      IF(IA.EQ.1) GO TO 29
      LX = -1 ; LY = 1 ; LX2 = 1 ; LY2 = -1
      XL2 = 0. ; YL2 = 0. ; NYC2 = 0
      IF(L1) PRINT,"READ HTX,XL,XS,NDX,NPX,SPX,ITX"
      READ(IN,FIN) HTX,XL,XS,NDX,NPX,SPX,ITX
      IF(SPX.LE.0.) SPX = 1. ; IF(ITX.EQ.0) ITX = 1
      IF(L1) PRINT,"READ HTY,NYC,NAY"
      READ(IN,FIN) HTY,NYC,NAY
      IF(HTX.LE.0.) GO TO 7
      IK = 1
      IF(L1) PRINT,"READ X-LABEL"
    1 READ(IN,FMT) LABT
      DO 2 I=1,60
      K = 61-I
      IF(LABT(K).NE.1H ) GO TO 3
    2 CONTINUE
    3 GO TO (6,8,26,28) ,IK
    6 ENCODE(LBX,FMT) (LABT(I),I=1,K)
      LX = -K
    7 IF(HTY.LE.0.) GO TO 9
      IK = 2
      IF(L1) PRINT,"READ Y-LABEL"
      GO TO 1
    8 ENCODE(LBY,FMT) (LABT(I),I=1,K)
      LY = K
    9 IF(IA.NE.2) GO TO 29
      IF(L1) PRINT,"READ HTX2,XL2,XS2,NDX2,NPX2,XY0"
      READ(IN,FIN) HTX2,XL2,XS2,NDX2,NPX2,XY0
      IF(L1) PRINT,"READ HTY2,NYC2,NAY2,YX0"
      READ(IN,FIN) HTY2,NYC2,NAY2,YX0
      IF(XY0.LE.0.) XY0 = NYC2*YCL
      IF(YX0.LE.0.) YX0 = SPX*XL
      IF(HTX2.LE.0.) GO TO 27
      IK = 3
      IF(L1) PRINT,"READ X-LABEL2"
      GO TO 1
   26 ENCODE(LBX2,FMT) (LABT(I),I=1,K)
      LX2 = K
   27 IF(HTY2.LE.0.) GO TO 29
      IK = 4
```

```
      IF(L1) PRINT,"READ Y-LABEL2"
      GO TO 1
   28 ENCODE(LBY2,FMT) (LABT(I),I=1,K)
      LY2 = -K
   29 CONTINUE
      Y0 = ALOG(YMIN)
      XSF = SPX/SFX
      YLF = .434294482*YCL
      IF(IDASH.NE.0) GO TO 12
      CALL PLOTS("A")
      CALL PLOT(X0,Y0,-3)
      DO 10 I = 1,N
      IF(Y(I).LE.0.) Y(I) = YMIN
      H = X(I)*XSF
      V = (ALOG(Y(I))-Y0)*YLF
      IF(I.EQ.1) CALL PLOT(H,V,3)
   10 CALL PLOT(H,V,2)
      GO TO 14
   12 IF(L1) PRINT,"DASHED LINE - SL1,SL2 = SOLID LENGTHS,",
     &         " BL = BLANK LENGTH (INCHES)"
      IF(L1) PRINT,"READ SL1,SL2,BL"
      READ(IN,FIN) SL1,SL2,BL
      CALL PLOTS("A")
      CALL PLOT(X0,Y0,-3)
      DO 13 I=1,N
      IF(Y(I).LE.0.) Y(I) = YMIN
      X(I) = X(I)*XSF
      Y(I) = (ALOG(Y(I))-Y0)*YLF
   13 CONTINUE
      CALL DASHED(X,Y,N,1.,1.,SL1,SL2,BL,0.)
   14 IF(IA-1) ,98,
      XS = XS*SPX
      IF(XL.LE.0.) GO TO 16
      XL = XL*SPX ; XST = XS*SFX/SPX
      CALL AXIS14(XS,YS,LBX,LX,HTX,XL,NDX,0,XST,SFX,SPX,
     &                ITX,NPX,0.)
   16 IF(NYC.LE.0) GO TO 17
      CALL LOGAXS(0.,0.,LBY,LY,HTY,YCL,NYC,1,YMIN,NAY,1)
   17 IF(XL2.LE.0.) GO TO 18
      XL2 = XL2*SPX ; XS2 = XS2*SPX
      XST2 = XS2*SFX/SPX
      CALL AXIS14(XS2,XY0,LBX2,LX2,HTX2,XL2,NDX2,0,XST2,SFX,SPX,
     &                ITX,NPX2,0.)
   18 IF(NYC2.LE.0) GO TO 98
      CALL LOGAXS(YX0,0.,LBY2,LY2,HTY2,YCL,NYC2,1,YMIN,NAY2,1)
   98 CALL PLOT(0.,0.,999)
   99 RETURN
      END
```

APPENDIX C: RESINV LISTING


```
** RUN *1ROSD441/PLOTS,E
      INTEGER E
      COMMON/Z1/E,M,N/Z2/DELX,SPAC/Z3/NS/Z4/I1,RMS,RMSC/Z5/IX
      COMMON/ZA1/Q(65,30)/ZA2/Q1(32,30)/ZA3/P(29)/ZA4/R(31),R2(31)/ZA5/
     &R1(31),P1(29)/ZA6/SN(30)
      DIMENSION NF(29),X(29)
C
C  CARD #1   ARRAY CHOICE, INPUT-
C          1--FOR SCHLUMBERGER,
C          2--FOR WENNER,
C           3--FOR BIPOLE-BIPOLE.
C   CARD #2   SPAC,E,M,NN,RMSC (FORMAT-FREE)
C           SPAC = CLOSEST A OR S SPACING (REAL)
C           E    = NUMBER OF MODEL LAYERS (INTEGER)
C           M    = NUMBER OF FIELD READINGS (INTEGER)
C           NN   = NUMBER OF FIXED PARAMETES (INTEGER)
C           RMSC = RMS PERCENT ERROR CUTOFF (REAL)
C   CARD #2A ENTER ONLY FOR BIPOLE-BIPOLE ARRAY, INPUT-
C           1--IF N-VALUES ARE VARIED,
C           0--IF A-SPACINGS ARE VARIED.
C   CARD #2B ENTER ONLY FOR BIPOLE-BIPOLE, IF VALUE ENTERED IN 2A WAS-
C           1--INPUT N-VALUES (TOTAL M) IN INCREASING ORDER (FORMAT-FREE)
C           0--INPUT ONE N-VALUE, (N.NE.1)
C   CARD #3   SKIP IF 1 WAS ENTERED ON CARD #2A,INPUT-
C           1--IF FIELD READINGS ARE PERFECTLY LOGARITHMIC ,
C           0--OTHERWISE.
C   CARD #3A ENTER ONLY IF 0 WAS ENTERED ON CARD #3,
C           INPUT A OR S-SPACINGS, (TOTAL M, FORMAT-FREE)
C           (ENTER EXTRA CARDS IF NECESSARY.)
C   CARD #4   ENTER FIELD APPARENT RESISTIVITY VALUES,
C           (FORMAT-FREE, ENTER EXTRA CARDS IF NECESSARY.)
C   CARD #5,  ENTER LAYER PARAMETERS, (TOTAL 2E-1, FORMAT-FREE)
C           ORDER-- H(1),H(2),...,H(E-1),R(1),R(2),...,R(E)
C   CARD #6   ENTER FIXED PARAMETER NUMBERS (SKIP IF NN=0),
C           SAME ORDER AS CARD #5,
C           I.E. FOR 4-LAYER MODEL-- IF H(3) AND R(2) FIXED, ENTER 3,5
C    *   *   *   *   *   *   *   *   *   *   *   *   *   *   *   *   *
C   REPEAT FOR ADDITIONAL MODELS.
C
 CALL FXOPT(89,1,1,0)
  5 FORMAT(V)
       DELX = ALOG(10.)/6.
 1000 READ 5,INDEX
       IF(INDEX.LE.0) STOP
       READ 5,SPAC,E,M,NN,RMSC
       IF(INDEX-2) 12,12,6
     6 READ 5, IX
       IF(IX.EQ.1) GO TO 9
       J=1
       GO TO 11
     9 J=M
    11 READ 5, (SN(I),I=1,J)
       GO TO 512
    12 IX=-1
   512 N=2*E-1
```

```
      SPAC=ALOG(SPAC)
      IF(IX.EQ.1) GO TO 13
      READ 5, INDX1
      IF(INDX1.EQ.1) GO TO 13
      CALL SPLINE(M)
      GO TO 14
   13 READ 5, (R2(I),I=1,M)
   14 READ 5, (P(I),I=1,N)
      IF(NN.LE.0) GO TO 41
      READ 5, (NF(I),I=1,NN)
   41 PRINT 42
   42 FORMAT(//" RESISTIVITY INVERSION PROGRAM")
      IF(INDEX-2)43,45,47
   43 PRINT 44
   44 FORMAT(/" SCHLUMBERGER ARRAY"/)
      GO TO 52
   45 PRINT 46
   46 FORMAT(/" WENNER ARRAY"/)
      GO TO 52
   47 PRINT 48
   48 FORMAT(/" BIPOLE-BIPOLE ARRAY"/)
      IF(IX.NE.1) GO TO 50
      SP=EXP(SPAC)
      PRINT 49,SP
   49 FORMAT(/5X"BIPOLE A-SPACING ="F6.2/)
      GO TO 52
   50 PRINT 51,SN(1)
   51 FORMAT(/5X"BIPOLE N-SPACING ="F6.2/)
   52 I1=0
      U=10.0
      V=1.5
   53 I1MAX = 15
      JMAX=15
   60 K1=0
      J1=0
        IF(INDEX-2) 70,80,80
   70 CALL SCHLUM(K1)
      GO TO 100
   80 CALL WENBIP(K1,INDEX)
      IF(NN.LE.0) GO TO 100
      DO 95 I=1,NN
         K=NF(I)
         DO 90 J=1,M
   90       W(J,K)=0
   95 CONTINUE
  100 DO 120 I=1,M
          R(I)=W(I,N+1)
          R1(I)=ALOG(R2(I)/R(I))
          DO 110 J=1,N
  110        G(I,J)=W(I,J)/R(I)
  120     CONTINUE
        IF(I1.GT.0) GO TO 170
C  COMPUTE SUM OF SQUARES.
        PHI=0
        DO 130 I=1,M
```

```
  130     PHI=PHI+R1(I)*R1(I)
C  COMPUTE RMS PERCENT ERROR.
          RMS=0
          DO 140 I=1,M
  140     RMS=RMS+(1-R(I)/R2(I))*(1-R(I)/R2(I))
          RMS=100.*SQRT(RMS/M)
          CALL OUTPUT
          IF(RMS.LE.RMSC) GO TO 1000
C  COMPUTE INITIAL EPSILON.
          E1=0
          DO 160 I=1,M
              DO 150 J=1,N
  150           E1=E1+Q(I,J)*Q(I,J)
  160     CONTINUE
          E1=SQRT(E1/(M*N))
C  ORTHOGONAL FACTORIZATION.
  170 CALL ORFAC1
  180 CALL ORFAC2(E1)
      CALL BACKSUB
      IF(NN.LE.0) GO TO 200
      DO 190 I=1,NN
          J=NF(I)
  190     P1(J)=0
  200 DO 210 I=1,N
          X(I)=P(I)
          P(I)=P(I)+P1(I)
  210     IF(P(I).LE.0) P(I)=0.001
      K1=1
C  COMPUTE NEW MODEL APPARENT RESISTIVITIES.
       IF(INDEX-2) 220,230,230
  220 CALL SCHLUM(K1)
      GO TO 250
  230 CALL WENBIP(K1,INDEX)
C  COMPUTE NEW SUM OF SQUARES.
  250 PHI1=0
      DO 260 I=1,M
          R(I)=Q(I,N+1)
          IF(R(I).LE.0) R(I)=0.001
          A=ALOG(R2(I)/R(I))
  260     PHI1=PHI1+A*A
C  COMPARE NEW AND OLD SUM OF SQUARES.
      IF(PHI1.LT.PHI) GO TO 280
C  INCREASE EPSILON.
      DO 275 I=1,N
  275 P(I)=X(I)
      E1=V*E1
      J1=J1+1
      IF(J1.LT.JMAX) GO TO 180
      WRITE(2,277)
  277 FORMAT(//" J1=JMAX...TRIAL MODEL WILL NOT CONVERGE."/)
      CALL OUTPUT
      GO TO 1000
  280 PHI=PHI1
C  COMPUTE RMS PERCENT ERROR.
      RMS=0
```

```
      DO 290 I=1,M
  290    RMS=RMS+(1-R(I)/R2(I))*(1-R(I)/R2(I))
      RMS=100.*SQRT(RMS/M)
      I1=I1+1
      IF(RMS.LE.RMSC) GO TO 320
      IF(I1.GE.I1MAX) GO TO 320
C  COMPUTE NEW EPSILON.
      IF(J1) 300,300,310
  300 E1=E1/U
  310 GO TO 60
  320 CALL OUTPUT
      GO TO 1000
      END
      SUBROUTINE SCHLUM(K1)
      INTEGER E
      COMMON/Z1/E,M,N/Z2/DELX,SPAC
      COMMON/ZA1/U(65,30)/ZA3/P(29)
      DIMENSION FLTR(29)
      DATA(FLTR (I),I=1,29)/.00046256,-.0010907,.0017122,-.002068/,
     &.0043046,-.0021236,.015995,.017065,.098105,.21918,.64722,1.1415,
     &.47819,-3.515,2.7743,-1.201,.4544,-.19427,.097364,-.054099,.031729
     &,-.019109,.011656,-.0071544,.0044042,-.002715,.0016749,-.0010335,
     &.00040124/
      Y=SPAC-19.*DELX-0.13069
      DO 20 I=1,M+29
         CALL TRANSFM(Y,I,K1)
   20    Y=Y+DELX
      J=1
      IF(K1.GT.0) J=N+1
      DO 30 I=J,N+1
   30    CALL FILTER(FLTR,29,I)
      RETURN
      END
      SUBROUTINE WENBIP(K1,INDEX)
      INTEGER E
      COMMON/Z1/E,M,N/Z2/DELX,SPAC/Z5/IX
      COMMON/ZA1/U(65,30)/ZA3/P(29)/ZA6/SN(30)
      DIMENSION FLTR(34),T(65)
      DATA(FLTR (I),I=1,34)/.000238935,.00011557,.00017034,.00024935,
     &.00036665,.00053753,.0007896,.0011584,.0017008,.0024959,.003664,
     &.0053773,.007893,.011583,.016998,.024934,.036556,.053507,.078121,
     &.11319,.16192,.22363,.28821,.30276,.15523,-.32026,-.53557,.51787,
     &-.196,.054394,-.015747,.0053941,-.0021446,.0000065125/
      S=ALOG(2.)
       IF(INDEX-2) 10,10,60
   10 Y=SPAC-10.8792495*DELX
      DO 55 I=1,M+33
         CALL TRANSFM(Y,I,K1)
         IF(K1.GT.0) GO TO 30
         DO 20 J=1,N
   20       T(J)=U(I,J)
   30    T(N+1)=U(I,N+1)
         Y1=Y+S
         CALL TRANSFM(Y1,I,K1)
         IF(K1.GT.0) GO TO 50
```

```
          DO 40 J=1,N
   40        Q(I,J)=2.*T(J)-Q(I,J)
   50     Q(I,N+1)=2.*T(N+1)-Q(I,N+1)
   55 Y=Y+DELX
          GO TO 160
   60 M1=1
      IF(IX.NE.1) GO TO 70
      M1=M
      M=1
   70 DO 150 I=1,M1
          Y=SPAC-10.8792495*DELX
          A=SN(I)
          B=1.
          IF(A.LT.1.) B=A*A+A-1.
          A1=ABS(A-1)
          S1=ALOG(A1)
          IF(A.LT.1.) Y=Y-ALOG(A)
          S2=ALOG(A)
          S3=ALOG(A+1.)
          DO 140 J=1,M+33
             Y1=Y+S1
             CALL TRANSFM(Y1,J,K1)
             IF(K1.GT.0) GO TO 90
             DO 80 K=1,N
   80         T(K)=Q(J,K)/A1
   90        T(N+1)=Q(J,N+1)/A1
             Y1=Y+S2
             CALL TRANSFM(Y1,J,K1)
             IF(K1.GT.0) GO TO 110
             DO 100 K=1,N
  100           T(K)=T(K)-2.*Q(J,K)/A
  110        T(N+1)=T(N+1)-2.*Q(J,N+1)/A
             Y1=Y+S3
          CALL TRANSFM(Y1,J,K1)
          IF(K1.GT.0) GO TO 130
          DO 120 K=1,N
  120           Q(J,K)=(T(K)+Q(J,K)/(A+1.))*A*(A+1.)*A1/(2.*B)
  130       Q(J,N+1)=(T(N+1)+Q(J,N+1)/(A+1.))*A*(A+1.)*A1/(2.*B)
  140        Y=Y+DELX
          IF(IX.NE.1) GO TO 150
          J=1
          IF(K1.GT.0) J=N+1
      DO 145 K=J,N+1
             CALL FILTER(FLTR,34,K)
  145 Q(I+34,K)=Q(1,K)
  150     CONTINUE
      IF(IX.NE.1) GO TO 160
      M=M1
      DO 154 I=1,M
          IF(K1.GT.0) GO TO 154
      DO 152 J=1,N
  152        Q(I,J)=Q(I+34,J)
  154     Q(I,N+1)=Q(I+34,N+1)
      GO TO 180
  160 J=1
```

```
      IF(K1.GT.0) J=N+1
      DO 170 I=J,N+1
 170     CALL FILTER(FLTR,34,I)
 180  RETURN
      END
      SUBROUTINE TRANSFM(Y,I,K1)
      INTEGER E
      COMMON/Z1/E,M,N
      COMMON/ZA1/Q(65,30)/ZA3/P(29)
      DIMENSION T(15)
      U=1./EXP(Y)
      T(1)=P(N)
      IF(K1.LE.0) Q(I,N)=1.
      DO 30 J=2,E
         A=EXP(-2.*U*P(E+1-J))
         B=(1.-A)/(1.+A)
         RS=P(N+1-J)
         TPR=RS*B
         T(J)=(TPR+T(J-1))/(1.+TPR*T(J-1)/(RS*RS))
         IF(K1.GT.0) GO TO 30
         C=T(J-1)/RS
         D=(1.+B*C)*(1.+B*C)
         Q(I,N+1-J)=(B*(1.-C*C)+2.*B*T(J-1)*(T(J-1)+TPR)/(RS*RS))/D
         Q(I,E+1-J)=((4.*U*RS*A /((1.+A)*(1.+A)))*(1.-C*C))/D
         AA=(1.-B*B)/D
         DO 20 K=(E+2-J),E
            IF(K.GE.E) GO TO 20
            Q(I,K)=Q(I,K)*AA
  20        Q(I,K+E-1)=Q(I,K+E-1)*AA
  30     CONTINUE
      Q(I,N+1)=T(E)
      RETURN
      END
      SUBROUTINE FILTER(FLTR,K,L)
      INTEGER E
      COMMON/Z1/E,M,N
      COMMON/ZA1/Q(65,30)
      DIMENSION RES(31),FLTR(K)
      DO 20 I=1,M
         RE=0
         DO 10 J=1,K
            R=FLTR(J)*Q(I+K-J,L)
  10        RE=RE+R
  20     RES(I)=RE
      DO 30 I=1,M
  30     Q(I,L)=RES(I)
      RETURN
      END
      SUBROUTINE ORFAC1
      INTEGER E
      COMMON/Z1/E,M,N/Z3/N3
      COMMON/ZA1/Q(65,30)
      N3=N
      IF(M.EQ.N) N3=N-1
      DO 60 I=1,N3
```

```
          I2=I+1
          S3=0
          DO 10 J=I,M
 10          S3=S3+Q(J,I)*Q(J,I)
          IF(S3.EQ.0) GO TO 60
          S3=SQRT(S3)
          IF(Q(I,I).GT.0) S3=-S3
          S4=1./SQRT(2.*S3*(S3-Q(I,I)))
          DO 20 J=I2,M
 20          Q(J,I)=-S4*Q(J,I)
          Q(M+1,I)=S4*(S3-Q(I,I))
          Q(I,I) = S3
          IF(I.EQ.N) GO TO 60
          DO 50 J=I2,N
             S1=Q(I,J)*Q(M+1,I)
             DO 30 K=I2,M
 30 S1=S1+Q(K,J)*Q(K,I)
             S1=-2.*S1
             Q(I,J)=Q(I,J)+S1*Q(M+1,I)
             DO 40 K=I2,M
 40             Q(K,J)=Q(K,J)+S1*Q(K,I)
 50          CONTINUE
 60       CONTINUE
       RETURN
       END
       SUBROUTINE ORFAC2(E1)
       INTEGER E
       COMMON/Z1/E,M,N
       COMMON/ZA1/Q(65,30)/ZA2/Q1(32,30)
       DO 80 I=1,N
          I2=I+1
          IF(I.EQ.N) GO TO 20
          DO 10 J=I2,N
 10          Q1(I,J)=0
 20       Q1(I,I)=E1
          S3=Q(I,I)*Q(I,I)
          DO 30 J=1,I
 30          S3=S3+Q1(J,I)*Q1(J,I)
          S3=SQRT(S3)
          IF(Q(I,I).GT.0) S3=-S3
          S4=1./SQRT(2.*S3*(S3-Q(I,I)))
          Q1(N+2,I)=S4*(S3-Q(I,I))
          DO 40 J=1,I
 40          Q1(J,I)=-S4*Q1(J,I)
          Q1(I2,I)=S3
          IF(I.EQ.N) GO TO 80
          DO 70 J=I2,N
             S1=Q(I,J)*Q1(N+2,I)
             DO 50 K=1,I
 50             S1=S1+Q1(K,J)*Q1(K,I)
             S1=-2.*S1
             DO 60 K=1,I
 60             Q1(K,J)=Q1(K,J)+S1*Q1(K,I)
 70          Q1(J+1,I)=Q(I,J)+S1*Q1(N+2,I)
 80       CONTINUE
```

```
      RETURN
      END
      SUBROUTINE BACKSUB
      INTEGER E
      COMMON/Z1/E,M,N/Z3/N3
      COMMON/ZA1/Q(65,30)/ZA2/G1(32,30)/ZA5/R1(31),P1(29)
      DIMENSION C(60)
C   CALCULATE C1,C2.
      DO 10 I=1,M
   10    C(I)=R1(I)
      DO 40 I=1,N3
         S1=C(I)*Q(M+1,I)
         DO 20 J=I+1,M
   20       S1=S1+C(J)*Q(J,I)
         S1=-2.*S1
         C(I) =C(I)+S1*Q(M+1,I)
         DO 30 J=I+1,M
   30       C(J)=C(J)+S1*Q(J,I)
   40    CONTINUE
C   CALCULATE C3,C2,C4.
      DO 50 I=1,N
   50    C(M+I)=0
      DO 80 I=1,N
         S1=G1(N+2,I)*C(I)
         DO 60 J=1,I
   60       S1=S1+C(M+J)*G1(J,I)
         S1=-2.*S1
         C(I)=C(I)+S1*G1(N+2,I)
         DO 70 J=1,I
   70       C(M+J)=C(M+J)+S1*G1(J,I)
   80    CONTINUE
C   CALCULATE DELTA-P.
      DO 85 I=1,N
   85 P1(I)=0
      P1(N)=C(N)/G1(N+1,N)
      P1(N-1)=(C(N-1)-G1(N+1,N-1)*P1(N))/G1(N,N-1)
      DO 100 I=3,N
         J=N-I+1
         S1=0
         DO 90 K=J+1,N
   90       S1=S1+G1(K+1,J)*P1(K)
  100    P1(J)=(C(J)-S1)/G1(J+1,J)
      RETURN
      END
      SUBROUTINE OUTPUT
      INTEGER E
     DIMENSION S2(100),C(100),SS2(100),S3(100)
      COMMON/Z1/E,M,N/Z2/DELX,SPAC/Z4/I1,RMS,RMSC/Z5/IX
      COMMON/ZA4/R(31),R2(31)/ZA3/P(29)/ZA6/SN(30)
    1 FORMAT(V)
      PRINT 100,I1
  100 FORMAT(///" ITERATION NO.",1X,I2//)
      PRINT 20
   20 FORMAT("LAYER NO.",6X,"THICKNESS",3X," RESISTIVITY",5X,
     &9HTHICK*RES,3X,9HTHICK/RES/)
```

```
      DO 40 I=1,E-1
         J=I
         D1=P(I)*P(I+E-1)
         D2=P(I)/P(I+E-1)
      PRINT 30,J,P(I),P(I+E-1),D1,D2
   30 FORMAT(4X,I2,12X,F6.2,5X,F8.3,8X,F8.3,4X,F8.3/)
   40 CONTINUE
      PRINT 50, E,P(N)
   50 FORMAT(4X,I2,23X,F8.3//)
      IF(IX.NE.1) GO TO 56
      PRINT 53
   53 FORMAT(/18X,"N",6X,"MODEL RHO",3X,"FIELD RHO"//)
      GO TO 75
   56 X=SPAC
      DO 60 I=1,M
      SN(I)=EXP(X)
   60 X=X+DELX
      PRINT 70
   70 FORMAT(/15X,"SPACING",3X,"MODEL RHO",3X,"FIELD RHO"//)
   75 DO 90 I=1,M
      PRINT 80,SN(I),R(I),R2(I)
   80 FORMAT(14X,F8.3,3X,F8.3,3X,F8.3)
   90 CONTINUE
      PRINT 110,RMS
  110 FORMAT(//10X,"RMS ERROR =",F8.3////)
     PRINT, "PLOT INITIAL MODEL OR BEST FIT FINAL MODEL"
    CALL PLOT2(SN,R,M)
     PRINT, "DO YOU WANT TO PLOT THE FIELD DATA YES(1); NO(2)"
     READ 1, III
     IF(III.EQ.2) GO TO 120
    CALL PLOT2(SN,R2,M)
 120 CONTINUE
      RETURN
      END
      SUBROUTINE SPLINE(M)
      COMMON/Z2/DELX,SPAC
      COMMON/Z44/R(31),R2(31)
      DIMENSION B(30),C(30),DELY(30),DELSQY(30),H(30),H2(30)
      DIMENSION S2(30),S3(30),SS2(31),T(31),X(31),Y(31)
      N=M
      READ 1,(X(I),I=1,N)
    1 FORMAT(V)
      DO 150 I=1,N
  150 X(I)=ALOG(X(I))
      READ 1,(Y(I),I=1,N)
      SPAC=X(1)
      M=INT((X(N)-SPAC)/DELX)+1
      A=SPAC
      DO 300 I=1,M
      T(I)=A
  300 A=A+DELX
      EPSLN=.00001
      N1=N-1
      DO 51 I=1,N1
      H(I)=X(I+1)-X(I)
```

```
   51 DELY(I)=(Y(I+1)-Y(I))/H(I)
      DO 52 I=2,N1
      H2(I)=H(I-1)+H(I)
      B(I)=.5*H(I-1)/H2(I)
      DELSQY(I)=(DELY(I)-DELY(I-1))/H2(I)
      S2(I)=2.*DELSQY(I)
   52 C(I)=3.*DELSQY(I)
      S2(1)=0.
      S2(N)=0.
      OMEGA=1.0717968
    5 ETA=0.
      DO 10 I=2,N1
         W=(C(I)-B(I)*S2(I-1)-(.5-B(I))*S2(I+1)-S2(I))*OMEGA
      IF(ABS(W)-ETA) 10,10,9
    9    ETA=ABS(W)
   10    S2(I)=S2(I)+W
      IF(ETA-EPSLN)14,5,5
   14 DO 53 I=1,N1
   53    S3(I)=(S2(I+1)-S2(I))/H(I)
      DO 61 J=1,M
         I=1
         IF(T(J)-X(1))58,17,55
   55 IF(T(J)-X(N)) 57,59,58
   56 IF(T(J)-X(I)) 60,17,57
   57    I=I+1
         GO TO 56
   58    WRITE(2,44) J
   44    FORMAT(I3,"TH ARGUMENT OUT OF RANGE")
         GO TO 61
   59    I=N
   60    I=I-1
   17    HT1=T(J)-X(I)
         HT2=T(J)-X(I+1)
         PROD=HT1*HT2
         SS2(J)=S2(I)+HT1*S3(I)
         DELSQS=(S2(I)+S2(I+1)+SS2(J))/6.
         R2(J)=Y(I)+HT1*DELY(I)+PROD*DELSQS
   61    CONTINUE
      RETURN
      END
```

APPENDIX D: RESDAT LISTING

```
RESDAT                    14:40: 1  05/26/82        FILE PAGE NO.   1

** RUN *;ROSD441/PLOTS,E;ROGHG546/RESINVS,E
          CHARACTER*72 PUS
        DIMENSION X(100),R(100),RA(100),ASP(100),RASUM(100)
         DIMENSION CP(100),S(100),RINV(100)
          REAL LL,L(100)
         PRINT 100
    100  FORMAT('INPUT SURVEY TYPE--1= WENNER PROFILING;2= SCHLUMBERGER
         & PROFILING; 3= WENNER SOUNDING; 4= SCHLUMBERGER SOUNDING;
         &5= POLE- DIPOLE')
          READ 110,I
    110   FORMAT(V)
          GO TO (1000,2000,3000,4000,5000),I
C    1000 WENNER PROFILING SURVEY
    1000 PRINT 120
    120   FORMAT('A=SPACING=;NUMBER OF POINTS=')
          READ 110,A,N
          PRINT 130
    130   FORMAT('INPUT PROFILE COORDINATE,RESISTANCE PAIRS--X1,R1,X2,R2,...')
          READ 110,(X(I),R(I),I=1,N)
          PRINT 140
    140   FORMAT('IS FACTOR 2PI INCLUDED IN RESISTANCE DATA YES(1),NO(2)')
          READ110,IPI
          IF(IPI.EQ.1)F=1.0
          IF(IPI.EQ.2)F=6.28319
          DO 150 I=1,N
    150   RA(I)=F*R(I)*A
          PRINT 160,A
    160   FORMAT('WENNER PROFILE--A=',F6.1//)
          PRINT 170
    170   FORMAT(20X,"X",10X,"RHO")
          PRINT 180,(X(I),RA(I),I=1,N)
    180   FORMAT(15X,F10.4,F10.4)
          CALL PLOT2(X,RA,N)
          PRINT 190
    190   FORMAT("ANOTHER PROFILE YES(1) NO(2)")
          READ 110,II
          IF(II.EQ.1)GOTO1000
          IF(II.EQ.2)GOTO6000
C   2000 SCHLUMBERGER PROFILING SURVEY
    2000 PRINT 200
    200   FORMAT("S=SPACING=;L=SPACING=;NUMBER OF POINTS=  ")
          READ 110,SS,LL,N
          PRINT 130
          READ 110,(X(I),R(I),I=1,N)
          PRINT 140
          READ 110, IPI
          IF(IPI.EQ.1)F=0.5
          IF(IPI.EQ.2)F=3.14159
          DO 210 I=1,N
    210   RA(I)=F*R(I)*SS*((LL/SS)**2 - 0.25)
          PRINT 220,SS,LL
    220   FORMAT("SCHLUMBERGER PROFILE--L=",F6.1,";S=",F6.1//)
          PRINT 170
          PRINT 180,(X(I),RA(I),I=1,N)
          CALL PLOT2(X,RA,N)
```

```
      PRINT 190
      READ 110,II
      IF(II.EQ.1)GOTO 2000
      IF(II.EQ.2)GOTO 6000
C 3000 WENNER SOUNDING SURVEY
 3000 PRINT 230
 230  FORMAT("INPUT SOUNDING LOCATION INFORMATION,UP TO 72 CHARACHTERS")
      READ 240, POS
 240  FORMAT(A72)
      PRINT 260
 260  FORMAT("INPUT NUMBER OF DATA POINTS")
      READ 110,N
      PRINT 270
 270  FORMAT("INPUT A-SPACING,RESISTANCE PAIRS--A1,R1,A2,R2,...")
      READ 110,(ASP(I),R(I),I=1,N)
      PRINT 140
      READ 110,IPI
      IF(IPI.EQ.1)F=1.0
      IF(IPI.EQ.2)F=6.28319
      DO 280 I=1,N
 280  RA(I)= F*ASP(I)*R(I)
     PRINT 290, POS
 290  FORMAT("WENNER SOUNDING"//A72//)
      PRINT 300
300  FORMAT(16X,"A",8X,"RHO")
     PRINT 310,(ASP(I),RA(I),I=1,N)
310  FORMAT(10X,F10.4,F10.4)
     PRINT,"DO YOU WANT LINEAR(TYPE 1) OR LOG-LOG(TYPE 2) PLOTS"
     READ 110,III
     IF(III.EQ.2) GO TO 313
     CALL PLOT2(ASP,RA,N)
     GO TO 315
313  CALL PLOTLL(ASP,RA,N)
315  PRINT,"DO YOU WANT A CUMULATIVE SUM PLOT YES(1),NO(2)"
     READ 110, KK
     IF(KK.EQ.2) GO TO 319
     RASUM(1)=RA(1)
     DO 317 I=2,N
       RASUM(I)=RASUM(I-1)+RA(I)
 317 CONTINUE
     PRINT 318,RASUM(N)
 318 FORMAT("MAX. CUMULATIVE RESISTIVITY VALUE = ",F8.2)
     PRINT,"PLOT CUMULATIVE RESISTIVITY VS. A-SPACING DATA"
     CALL PLOT2(ASP,RASUM,N)
      PRINT,"DO YOU WANT AN INVERSE RESISTIVITY PLOT YES(1),NO(2)"
      READ 110,KKK
      IF(KKK.EQ.2) GO TO 319
      DO 325 I=1,N
325   RINV(I)=1./(F*R(I))
      PRINT 316, RINV(N)
316   FORMAT(//"MAX. VALUE OF INVERSE RESISTIVITY = ",F10.6//)
      CALL PLOT2(ASP,RINV,N)
 319 PRINT 320
320   FORMAT("DO YOU WISH TO INTERPRET DATA YES(1), NO(2)")
       READ 110,JJ
```

```
           IF(JJ.EQ.2) GO TO 6000
         INDE=2
         SPA=ASP(1)
         INDX=0
         CALL RESINVS(ASP,RA,N,INDE,SPA,INDX)
           PRINT 330
     330 FORMAT('ANOTHER SOUNDING YES(1), NO(2)')
           READ 110,JJ
           IF(JJ.EQ.1) GO TO 3000
           IF(JJ.EQ.2) GO TO 6000
C 4000      SCHLUMBERGER SOUNDING
    4000 PRINT 230
          READ 240,POS
          PRINT 140
          READ 110, IPI
          IF(IPI.EQ.1) F=0.5
          IF(IPI.EQ.2) F=3.14159
    4010 PRINT 4020
    4020 FORMAT('INPUT NO. OF DATA POINTS')
          READ 110, N
          PRINT 4030
    4030 FORMAT('INPUT S-SPACING, L-SPACING, RESISTANCE DATA')
          READ 110,(S(I),L(I),R(I), I=1,N)
          DO 4040 I=1,N
    4040 RA(I)=F*R(I)*S(I)*((L(I)/S(I))**2 - 0.25)
          PRINT 4045, POS
    4045 FORMAT(///'SCHLUMBERGER SOUNDING'//A72//)
          PRINT 4050
    4050 FORMAT(20X,"S",5X,"L",10X,"RHO")
          PRINT 4060,(S(I),L(I),RA(I), I=1,N)
    4060 FORMAT(16X,F5.1,2X,F6.1,6X,F10.4)
          PRINT,'DO YOU WANT TO PLOT APPARENT RESISTIVITY VS. L-SPACING'
         PRINT,'LINEAR(TYPE 1) OR LOG-LOG(TYPE 2)'
         READ 110, NNN
         IF(NNN.EQ.2) GO TO 4065
          CALL PLOT2(L,RA,N)
         GO TO 4067
    4065 CALL PLOTLL(L,RA,N)
    4067 PRINT,'DO YOU WANT TO INTERPRET DATA YES(1),NO(2)----
         & IF SO, ONLY ONE S-VALUE SHOULD BE IN DATA OR THERE SHOULD
         & BE NO JUMPS IN THE SOUNDING CURVE'
          READ 110, III
          IF(III.EQ.1) GO TO 4080
    4070 PRINT, 'DO YOU WANT TO INPUT DATA FOR ANOTHER SOUNDING'
          READ 110,JJJ
          IF(JJJ.EQ.1) GO TO 4000
          GO TO 6000
    4080 CONTINUE
          INDE=1
          SPA=L(1)
          INDX=0
          CALL RESINVS(L,RA,N,INDE,SPA,INDX)
          GO TO 4070
    5000 CONTINUE
C         POLE-DIPOLE SURVEY
```

```
      PRINT 5010
 5010 FORMAT('POLE-DIPOLE CURRENT STATION/PROFILE DIRECTION INFORMATION
     & UP TO 72 CHARACTERS')
      READ 240, POS
      PRINT 140
      READ 110,IPI
      IF(IPI.EQ.1) F=1.0
      IF(IPI.EQ.2) F=6.28319
      PRINT 5020
 5020 FORMAT('INPUT POTENTIAL ELECTRODE SPACING AND NUMBER OF
     & DATA VALUES')
      READ 110,PP,N
      PRINT,"INPUT--DISTANCE TO FIRST POTENTIAL ELECTRODE, RESISTANCE
     & PAIRS"
      READ 110,(CP(I),R(I),I=1,N)
      PRINT,'POLE-DIPOLE SURVEY'
      PRINT 5025, POS
 5025 FORMAT(//A72///)
      PRINT 5027
 5027 FORMAT(14X,'C1P1,C1P2',10X,'RHO'//)
      DO 5030 I=1,N
      RA(I)=(F*CP(I)*(CP(I)+PP)/PP)*R(I)
      PRINT 5040, CP(I),CP(I)+PP,RA(I)
 5030 CONTINUE
 5040 FORMAT(10X,F6.1,F6.1,5X,F10.4)
      PRINT, "PLOT APPARENT RESISTIVITY VERSUS X--X AT MIDPOINTS
     & OF PP-LOCATIONS"
      DO 5050 I=1,N
 5050 X(I)=CP(I)+PP/2
      CALL PLOT2(X,RA,N)
      PRINT,"DO YOU WANT TO INPUT ANOTHER DATA SET"
      READ 110,II
      IF(II.EQ.1) GO TO 5000
      IF(II.EQ.2) GO TO 6000
 6000 CONTINUE
      STOP
      END
```

APPENDIX E: TIDES LISTING

```
TIDES                    14:28:20  05/26/82        FILE PAGE NO.   1

5** RUN *ROSD441/PLCTS,E
10C THIS PROGRAM COMPUTES THE THEORETICAL GRAVITY TIDE FOR ANY POINT
20C ON THE SURFACE OF A RIGID EARTH AS A FUNCTION OF TIME.
30C A COMPLIANCE FACTOR OF 1.16 HAS BEEN INCLUDED.
40C INPUT DATA ARE IN FREE FIELD FORMAT...
50C INPUT DATA IDENTIFIED BY COMMENTS JUST PRIOR TO READ STATEMENTS.
60C
65         CHARACTER *8XINPUT(3)
70        DIMENSION DAYPM(12),G(5000)
72   REAL MINUTE(5000)
75         DATA XINPUT(1),XINPUT(3)/1H/,1H:/
80        DOUBLE PRECISION CDEGTR,CMINTR,CSECTR,PI2,SC1,PC1,HC1,ANC1,S,P,H,
90       &P1,AN,STOR,T,SMINP,S2MP,SMINN,HMINP1,SMINP2,SMINH2,CHI,CHI1,ALSUN,
100       &ALPHA,XI,SIGMA,ALMOON,ARG6,ARG7,ARG9,ARG10,E1,E11,E12,E13,C,C1,
110       &APRIME,APRIM1,DISTES,DISTEM,DAYS1,DAYS2,DAYS3,DAYS4,DAYS5,DAYS6
115          M=0
120         CDEGTR=1.745329251994 3D-2
130         CMINTR=2.908882086660D-4
140         CSECTR=4.848136811D-6
150          DATA C,C1,E/3.84402D10,1.495D13,.05490/
160          DATA AMU,AMMOON,AMSUN/6.670E-8,7.3537E25,1.993E33/
170          DATA E11,E12,E13/1.675104D-2,4.180D-5,1.26D-7/
180         RATIO=.074804
190         OMEGA=23.452*CDEGTR
200         SMALLA=6.37827E8
240         PI2=6.283185307200
250         SC1=1108411.2D0
260         PC1=392515.94D0
270         HC1=129602768.13D0
280         ANC1=482912.63D0
313C INPUT NAME OF OUTPUT DATA FILE
325          CALL ATTACH(4,XINPUT,3,0,,)
326     80 FORMAT (V)
328C INPUT NUMBER OF TIDE DATA SETS(NCOMP) AND TIME INCREMENT(MM)
330          READ 10, NCOMP,MM
340         DO 400 JJ=1,NCOMP
350          PRINT 10, JJ
353C INPUT LATITUDE IN DEGREES(SLATD) AND DECIMAL MINUTES(SLATM) AND
354C SIMILARLY FOR LONGITUDE(SLONGD,SLONGM).  INPUT ELEVATION IN
355C METERS(SELEV).  INPUT DATE IN MONTH(DATEM), DAY(DATED, AND
357C YEAR(DATEY).   INPUT STARTING TIME IN HOUR(TIMEH) AND MINUTE(TIMEM)
358C GREENWICH TIME.
360         READ 20,  SLATD,SLATM,SLONGD,SLONGM,SELEV,DATEM,DATED,DATEY,TIMEH
370        &,TIMEM
375C INPUT TOTAL NUMBER OF TIME INCREMENTS TO BE CALCULATED(NTOTAL)
376C THUS THE TOTAL LENGTH OF TIDAL RECORD TO BE CALCULATED=MM X NTOTAL
380         READ 10, NTOTAL
385          WRITE (4,5) NTOTAL
390         DO600 KK=1,NTOTAL
400         IF(KK.EQ.1) GO TO 75
410         MINUTE(KK)=MINUTE(KK-1)+MM
420         DAYS5=MINUTE(KK)/(24.*60.)
430         GO TO 350
440     75 DAYS2=0.
450         ALAMBD=SLATD*CDEGTR+SLATM*CMINTR
```

```
      ALONG=SLONGD+SLONGM/60.
      ELEV=SELEV*100.
      MONTH=DATEM
      IDAY=DATED
      IYEAR=DATEY
      IHOUR=TIMEH
      MINUTE(KK)=TIMEM
C  CALCULATE T (NUMBER OF JULIAN CENTURIES)
      DATA DAYPM/31.,28.,31.,30.,31.,30.,31.,31.,30.,31.,30.,31./
      DO 100 I=1,12
      JS=MONTH-I
      IF(JS.EQ.0) GO TO 150
  100 DAYS2=DAYS2+DAYPM(I)
  150 DAYS3=IDAY-1
      DAYS4=IHOUR/24.
      DAYS5=MINUTE(KK)/(24.*60.)
      DAYS1=IYEAR*365.
      NYEAR=IYEAR/4
      SJ=IYEAR/4.-NYEAR
      IF(SJ.GT.0) GO TO 200
      IF(MONTH-2) 300,300,200
  200 DAYS6=NYEAR
      GO TO 350
  300 DAYS6=NYEAR-1.
  350 CONTINUE
      STOR=DAYS1+DAYS2+DAYS3+DAYS4+DAYS5+DAYS6+.5
      T=STOR/36525.
      S=270.D0*CDEGTR+26.D0*CMINTR+14.72D0*CSECTR+((.0068D0*CSECTR*T+
     &9.09D0*CSECTR)*T+1336.D0*PI2+SC1*CSECTR)*T
      P=334.D0*CDEGTR+19.D0*CMINTR+40.87D0*CSECTR+(((-.045D0)*CSECTR*T
     &-37.24D0*CSECTR)*T+11.D0*PI2+PC1*CSECTR)*T
      H=279.D0*CDEGTR+41.D0*CMINTR+48.04D0*CSECTR+(1.089D0*CSECTR*T+
     &HC1*CSECTR)*T
      AN=259.D0*CDEGTR+10.D0*CMINTR+57.12D0*CSECTR+((.008D0*CSECTR*T+
     &7.58D0*CSECTR)*T-5.D0*PI2-ANC1*CSECTR)*T
      P1=281.D0*CDEGTR+13.D0*CMINTR+15.D0*CSECTR+((.012D0*CSECTR*T+
     &1.63D0*CSECTR)*T+6189.03D0*CSECTR)*T
      E1=E11-(E12+E13*T)*T
      ARG1=1./(1.+.006738*(SIN(ALAMBD)**2))
      CAPC=SQRT(ARG1)
      RADIUS=CAPC*SMALLA+ELEV
      APRIME=1./(C*(1.-E**2))
      APRIM1=1./(C1*(1.-E1**2))
      SMINP=S-P
      S2HP=S-2*H+P
      SMINH=S-H
      HMINP1=H-P1
      SMINP2=2.*SMINP
      SMINH2=2.*SMINH
      DISTEM=1./C+APRIME*E*DCOS(SMINP)+APRIME*(E**2)*DCOS(SMINP2)
     &+15*APRIME*RATIO*E*DCOS(S2HP)/8.+APRIME*(RATIO**2)*DCOS(SMINH2)
      DISTES=1./C1+APRIM1*E1*DCOS(HMINP1)
      TZERO=IHOUR+MINUTE(KK)/60.
      SMALLT=(15.*(TZERO-12.)-ALONG)*CDEGTR
       CHI1=SMALLT+H
```

```
      ALSUN=H+2.*E1*DSIN(HMINP1)
      ARG2=5.145*CDEGTR
      ARG3=COS(OMEGA)*COS(ARG2)-SIN(OMEGA)*SIN(ARG2)*DCOS(AN)
      AI=ARCOS(ARG3)
      ARG4=SIN(ARG2)*DSIN(AN)/SIN(AI)
      ANU=ARSIN(ARG4)
      CHI=SMALLT+H-ANU
      SALPHA=SIN(OMEGA)*DSIN(AN)/SIN(AI)
      CALPHA=DCOS(AN)*COS(ANU)+DSIN(AN)*SIN(ANU)*COS(OMEGA)
      CALPH1=1+CALPHA
      ALPHA=2*ATAN2(SALPHA,CALPH1)
      XI=AN-ALPHA
      SIGMA=S-XI
      ALMOON=SIGMA+2.*E*DSIN(SMINP)+5.*(E**2)*DSIN(SMINP2)/4.
     &+15.*RATIO*E*DSIN(S2HP)/4.+11.*(RATIO**2)*DSIN(SMINH2)/8.
      ARG5=(OMEGA/2.)
      ARG6=ALSUN-CHI1
      ARG7=ALSUN+CHI1
      CPHI=SIN(ALAMBD)*SIN(OMEGA)*DSIN(ALSUN)+COS(ALAMBD)*((COS(ARG5)**2
     &*DCOS(ARG6)+(SIN(ARG5)**2)*DCOS(ARG7)))
      ARG8=(AI/2.)
      ARG9=ALMOON-CHI
      ARG10=ALMOON+CHI
      CTHETA=SIN(ALAMBD)*SIN(AI)*DSIN(ALMOON)+COS(ALAMBD)*((COS(ARG8)**2
     &)*DCOS(ARG9)+(SIN(ARG8)**2)*DCOS(ARG10))
      GM=AMU*AMMOON*RADIUS*(3.*(CTHETA**2)-1.)*(DISTEM**3)+3*(AMU*AMMOON
     &*(RADIUS**2)*(5.*(CTHETA**3)-3.*CTHETA))*(DISTEM**4)/2.
      GM=GM*1000.
      GS=AMU*AMSUN*RADIUS*(3.*(CPHI**2)-1)*(DISTES**3)*1000.
      GZERO=GM+GS
     G(KK)=GZERO*1160.
       M=M+1
  600 WRITE(4,90) M,MINUTE(KK),G(KK)
      PRINT65, SLATD,SLATM,SLONGD,SLONGM ,DATEM,DATED,DATEY,TIMEH,
     &TIMEM
      PRINT 70,  (G(LL), LL=1,NTOTAL)
CALL PLOT2(MINUTE,G,NTOTAL)
  400 CONTINUE
    5 FORMAT(I4)
   10 FORMAT(V)
   20 FORMAT(V)
   50 FORMAT(3F15.5)
   65 FORMAT(1X,F3.0,F5.2,F4.0,F5.2,5F3.0)
   70 FORMAT('0',12F6.1,/12F6.1)
   90 FORMAT(I3,I5,F15.3)
STOP
END
```

APPENDIX F: TALGRAD LISTING


```
** RUN *;H08D441/PLOTS,E
C  TALGRAD COMPUTES GRAVITY AND GRAVITY GRADIENT PROFILES OVER TWO-
C  DIMENSIONAL POLYGONAL CROSS-SECTION MODELS
       DIMENSION XXX(40),XX(200),X(40),Z(40),R(40),A(40),B(40),
     &S(40),U(40),V(40),T(40),W(40),GG(40),GTC(10,200),GTT(10,200),
     &BA(200),H(10),DELGTZ(200),DELGTX(200)
      DIMENSION G(200),XHG(200),AS(200)
      DIMENSION DELGTZP(200)
      PRINT ,"K,DELX,DELZ,ZMAX"
      READ 10, K,DELX,DELZ,ZMAX
10     FORMAT(V)
       DO 20 M=1,K
20     XX(M)=DELX*(M-1)
       PRINT ,"NPOLY"
       READ 30,NPOLY
30     FORMAT(V)
      PRINT 40
40    FORMAT('DIMENSION IN KFT(TYPE 1) OR METERS(TYPE 2)')
      READ 50,NN
50    FORMAT(V)
      IF(NN.EQ.1) C=4.067
      IF(NN.EQ.2) C=13.34E-3
      DO 70 II=1,10
      DO 60 NG=1,200
60    GTT(II,NG)=0.0
70    CONTINUE
      H(1)=0.0
      DO 1000 II=1,10
       DO 295  L=1,NPOLY
       PRINT 73,L
 73   FORMAT('POLYGON--',I2/)
       PRINT, "DELRO,N"
READ 80, DELRO,N
80    FORMAT(V)
       PRINT ,"X1,Z1,.....,XN,ZN"
      READ 100,(XXX(M),Z(M), M=1,N)
100    FORMAT(V)
       IF(II.GT.1) GO TO 145
       PRINT 110
110    FORMAT(//25X,'STATIONS    POLYG. SIDES     DENSITY'/)
       PRINT 120,K,N,DELRO
120    FORMAT(I30,I10,F20.6//)
       PRINT 130
130    FORMAT(21X,6HVERTEX,7X,12HDISTANCE    ,9X,9HDEPTH    )
       PRINT 140,(M,XXX(M),Z(M),M=1,N)
140    FORMAT(I25,2F20.6)
145    NN=N+1
       XXX(NN)=XXX(1)
       Z(NN)=Z(1)
150    DO 160 NG=1,200
160    GTC(II,NG)=0.0
       DO 290 NG=1,K
       DO 170 I=1,NN
       X(I)=XXX(I)-XX(NG)
170    CONTINUE
```

```
      DO 280 J=1,N
      JJ=J+1
      R(J)=X(J)**2+(Z(J)+H(II))**2
      R(JJ)=X(JJ)**2+(Z(JJ)+H(II))**2
      A(J)=X(JJ)-X(J)
      B(J)=Z(JJ)-Z(J)
      S(J)=X(J)*(Z(JJ)+H(II))-X(JJ)*(Z(J)+H(II))
      U(J)=A(J)**2 + B(J)**2
      V(J)=0.5*ALOG(R(JJ)/R(J))
      T(J)=X(J)*X(JJ)+(Z(J)+H(II))*(Z(JJ)+H(II))
      IF(S(J)) 180,250,200
  180 IF(T(J)) 190,230,220
  190 W(J)=-3.1415927 + ATAN(S(J)/T(J))
      GO TO 260
  200 IF(T(J)) 210,240,220
  210 W(J)=3.1415927 + ATAN(S(J)/T(J))
      GO TO 260
  220 W(J)=ATAN(S(J)/T(J))
      GO TO 260
  230 W(J)=-1.570796
      GO TO 260
  240 W(J)=1.570796
      GO TO 260
  250 W(J)=0.0
  260 GG(J)=(S(J)/U(J))*(B(J)*V(J)-A(J)*W(J))
  270 GPA=C*DELRO*GG(J)
      GTC(II,NG)=GTC(II,NG)+GPA
  280 CONTINUE
      GTT(II,NG)=GTT(II,NG)+GTC(II,NG)
      G(NG)=GTT(II,NG)
  290 CONTINUE
  295 CONTINUE
      PRINT 300, H(II)
  300 FORMAT('DO YOU WANT TO PRINT GZ FOR H=',F6.2,'--YES(1),NO(2)')
      READ 30,MM
      IF(MM.EQ.2) GO TO 305
      PRINT 310, H(II)
  310 FORMAT(//'-----ELEVATION = ',F10.6,'-----'//)
      PRINT 320
  320 FORMAT(15X,'STATION',10X,'X',10X,'GZ(X)',//)
      DO 1500 NG=1,K
 1500 PRINT 330,NG,XX(NG),GTT(II,NG)
  330 FORMAT(17X,I3,8X,F10.6,5X,F10.6)
  305 CONTINUE
      PRINT, "DO YOU WANT PLOTS OF GRAVITY PROFILES--YES(1), NO(2)"
      READ 10, NN
      IF(NN.EQ.2) GO TO 333
      PRINT 331,H(II)
  331 FORMAT('PLOT GRAVITY PROFILE FOR H=',F6.2/)
      CALL PLOT2(XX,G,K)
  333 IF(H(II).GE.ZMAX) GO TO 340
       H(II+1)=H(II)+DELZ
 1000 CONTINUE
  340 PRINT 350
  350 FORMAT('DO YOU WANT TO CALCULATE GRAVITY GRADIENTS
```

```
      &TYPE 1 FOR YES, 2 FOR NO')
      READ 360, NGRAD
  360 FORMAT(V)
      IF(NGRAD.EQ.2) GO TO 5000
  365 PRINT 370
  370 FORMAT('INPUT DESIRED INCREMENT VALUES FOR HORIZONTAL AND'/
     &'VERTICAL GRADIENT VALUES, DELXX AND DELZZ, IN INCREMENTS'/
     &'OF DELX AND DELZ---')
      READ 380, DELXX, DELZZ
  380 FORMAT(V)
      IX=DELXX/DELX
      IF(DELZ.EQ.0.0) GO TO 505
      IZ=DELZZ/DELZ
      DO 2500 NG=1,K
 2500 DELGTZ(NG)=(GTT(1,NG)-GTT(IZ+1,NG))/DELZZ
      PRINT 390,DELZZ
  390 FORMAT('-----DELTA-Z = ',F10.6//15X,'STATION',10X,'GZ,Z'//)
      DO 400 NG=1,K
  400 PRINT 500,NG,XX(NG),DELGTZ(NG)
  500 FORMAT(17X,I3,8X,F10.6,5X,F10.6)
    PRINT 502
  502 FORMAT('PLOT VERTICAL GRADIENT PROFILES')
      CALL PLOT2(XX,DELGTZ,K)
  505 PRINT 510
  510 FORMAT('INPUT VALUE OF H FOR WHICH THE HORIZONTAL GRADIENT'/
     &'IS DESIRED IN INCREMENT OF DELZ')
      READ 520,HZ
  520 FORMAT(V)
      NZ=HZ/DELZ
       IF(DELZ.EQ.0.0.OR.HZ.EQ.0.0) NZ=1
      DO 3000 NG=1,K-IX
      DELGTX(NG)=(GTT(NZ,IX+NG)-GTT(NZ,NG))/DELXX
      IF(IX+NG+1.GT.K) GO TO 530
 3000 CONTINUE
  530 PRINT 540,DELXX
  540 FORMAT('-----DELTA-X = ',F10.6//15X,'STATION',10X,
     &'GZ,X'//)
      DO 550 NG=1,K
      PRINT 560,NG,IX+NG,DELGTX(NG)
      XHG(NG)=(XX(IX+NG)+XX(NG))/2.
      IF(IX+NG+1.GT.K) GO TO 551
  550 CONTINUE
  551 PRINT 553
  553 FORMAT('PLOT HORIZONTAL GRADIENT PROFILE--PLOTTED AT MIDPOINTS'/
     &,'OF DELXX INTERVALS')
      KK=K-IX
      CALL PLOT2(XHG,DELGTX,KK)
  560 FORMAT(15X,I3,'-',I3,6X,F10.6,5X,F10.6)
      PRINT 562
  562 FORMAT('DO YOU WANT GRADIENT SPACE AND SQ. OF MODULUS OF ANALYTIC'/
     &,'SIGNAL PLOTS  ***IF SO, IX MUUST EQUAL 2***  YES(1), NO(2)')
      READ 580, MMM
      IF(MMM.EQ.2) GO TO 570
      DO 565 I=1,K
      DELGTZP(I)=DELGTZ(I+1)
```

```
     IF(I+1.EQ.K-1) GO TO 567
565 CONTINUE
567 CONTINUE
     DO 568 I=1,KK
568 AS(I)= DELGTX(I)**2 + DELGTZP(I)**2
     CALL PLOT2(DELGTZP,DELGTX,KK)
    CALL PLOT2(XMG,AS,KK)
570 CONTINUE
     PRINT ,"DO YOU WANT TO RECALCULATE GRADIENTS FOR OTHER VALUES OF"
     PRINT, "DELXX AND DELZZ  YES(1), NO(2)"
     READ 580, NNN
580 FORMAT(V)
     IF(NNN.EQ.1) GO TO 365
5000 CONTINUE
STOP
END
```

APPENDIX G: HILBERT LISTING

```
HILBERT                  141471 5  05/26/82        FILE PAGE NO.    1

** RUN *;R0SD441/PLOTS,E
      DIMENSION T(100),H(100),X(100)
       DIMENSION A(100)
     READ 10,N,DELX
      X(1)=.5*DELX
      DO 7 I=2,N
  7  X(I)=X(I-1) + DELX
     READ 10, (T(I), I=1,N)
 10  FORMAT(V)
      DO 20 I=1,N
        CALL HILBRT(T,N,H,A)
 20   CONTINUE
      PRINT 25
  25   FORMAT(10X,"X",12X,"GZ,X",12X,"GZ,Z",12X,"A")
       PRINT 30,(X(I),T(I),H(I),A(I),I=1,N)
  30   FORMAT(5X,F10.4,F15.8,F15.8,F15.8)
       PRINT, "DO YOU WANT GRADIENT PROFILES YES(1), NO(2)"
       READ 10, MM
       IF(MM.EQ.2) GO TO 33
      CALL PLOT2(X,H,N)
      CALL PLOT2(X,T,N)
 33   PRINT, "DO YOU WANT A GRADIENT SPACE PLOT YES(1), NO(2)"
      READ 10, NN
      IF(NN.EQ.2) GO TO 35
      CALL PLOT2(H,T,N)
  35   PRINT, "DO YOU WANT A PLOT OF THE MODULUS OF THE ANALYTIC
      &       SIGNAL  YES(1), NO(2)"
       READ 10, LL
      IF(LL.EQ.2) GO TO 40
     CALL PLOT2(X,A,N)
 40    STOP
      END
SUBROUTINE HILBRT(T,N,H,A)
       DIMENSION T(1),H(1),A(1)
      DO 5 I=1,N
  5   T(N+2-I)=T(N+1-I)
      T(1)=0
      T(N+2)=0
      DO 40 I=1,N
      H(I)=0
      J=1
 10   IF(J.EQ.(N-I+1)) GO TO 20
      H(I)=H(I)+(T(I+J+1)*(J+1)-T(I+J+2)*J)*ALOG(1.+1./J)
      J=J+1
      GO TO 10
 20   J=1
 30   IF(J.EQ.I) GO TO 40
      H(I)=H(I)+(T(I-J)*J-T(I-J+1)*(J+1))*ALOG(1.+1./J)
      J=J+1
      GO TO 30
 40   H(I)=H(I)/3.141593
      DO 45 I=1,N
       T(I)=T(I+1)
45     A(I)=T(I)**2 + H(I)**2
       RETURN

HILBERT   CONT           141471 5  05/26/82        FILE PAGE NO.    2

      END
```

APPENDIX H: SEISDIG, SEISPLOT, REFINT, AND DOMER LISTINGS

SEISDIG 1

```
LIS
10 INIT
20 REM***************************************************************
30 REM*** THIS PROGRAM IS DESIGNED TO REDUCE SEISMIC REFRACTION *****
40 REM*** OSCILLOGRAPH RECORDS, AND WRITE THE RESULTING TIME-   *****
50 REM*** DISTANCE INFORMATION TO A MAGNETIC TAPE               *****
60 REM***************************************************************
100 PAGE
110 PRINT "INPUT FROM THE KEYBOARD IDENTIFICATION OF DATA"
120 PRINT "THIS INFORMATION MUST BE 72 CHARACTERS OR LESS"
130 INPUT X$
140 DIM G(24),T(24)
150 PRINT "INPUT COORDINATE OF SHOTHOLE IN FEET."
160 INPUT S1
170 PRINT "INPUT DISTANCE FROM SHOTHOLE TO GEOPHONE NEAREST IT."
180 PRINT "NOTE--USE NEGATIVE # IF MOVING FROM HIGH FOOTAGE TO "
190 PRINT "LOW FOOTAGE."
200 INPUT G(1)
210 PRINT "KEY IN THE SHOTHOLE DEPTH"
220 INPUT D2
230 G(1)=G(1)+S1
240 PRINT "INPUT THE SPACING BETWEEN GEOPHONES--USE NEGATIVE VALUE"
250 PRINT "IF MOVING FROM HIGH FOOTAGE TO LOW FOOTAGE."
260 INPUT S
270 REM***************************************************************
280 REM***** INITIALIZE OSCILLOGRAPH RECORD ***************************
290 REM***************************************************************
300 PRINT "DIGITIZE THE TIMING LINE JUST PRECEDING THE TIME BREAK"
310 INPUT @8:T1,D,D1
320 PRINT "G"
330 PRINT "DIGITIZE THE TIMING LINE OCCURING 200 msec LATER"
340 INPUT @8:T2,D,D1
350 PRINT "G"
360 T3=200/(T2-T1)
370 PRINT "DIGITIZE THE TIME BREAK"
```

SEISDIG 2

```
380 INPUT @8:T0,D,D$
390 PRINT "G"
400 PAGE
410 PRINT "DIGITIZE THE FIRST ARRIVALS OFF OSCILLOGRAPH RECORD"
420 PRINT "   1. PRESS WHITE BUTTON NORMALLY."
430 PRINT "   2. PRESS BUTTON #1 IF A TRACE IS SKIPPED"
440 PRINT "   3. PRESS BUTTON #2 TO REDIGITZE THE PRECEDING POINT"
450 PRINT "   4. PRESS BUTTON #3 TO DIGITIZE LAST POINT"
460 N=1
470 PRINT @32,26:2
480 PRINT "DIGITIZE TRACE # ";N
490 INPUT @8:T(N),Y,Z$
500 PRINT "GGG"
510 T(N)=(T(N)-T0)*T3
520 IF Z$="2" THEN 600
530 IF Z$="4" THEN 480
540 IF Z$="8" THEN 560
550 GO TO 570
560 G(N)=G(N)+S
570 G(N+1)=G(N)+S
580 N=N+1
590 GO TO 480
600 REM***************************************************************
610 REM****CORRECT DISTANCES FOR SHOTHOLE DEPTH USING PYTHAGOREAN*****
620 REM****THEOREM APPLIED TO FIRST FOUR GEOPHONES AND THEN      *****
630 REM****LIST THE TIME DISTANCE INFORMATION
640 REM***************************************************************
650 D3=D2↑2
660 FOR I=1 TO 4
670 L1=ABS(S1-G(I))↑2
680 IF S>0 THEN 710
690 G(I)=S1-SQR(L1+D3)
700 GO TO 720
710 G(I)=S1+SQR(L1+D3)
720 NEXT I
```

```
730 PAGE
740 Y$="
750 Y$=Y$&Y$
760 P=LEN(X$)
770 O=36-P/2
780 Y$=REP(X$,O,P)
790 PRINT Y$
800 PRINT @32,26:0
810 A$="TRACE NO."
820 B$="DISTANCE"
830 C$="TIME(msec)"
840 PRINT A$,B$,C$
850 PRINT "-----------------------------------------------------------"
860 PRINT
870 FOR I=1 TO N
880 PRINT I,G(I),T(I)
890 NEXT I
900 INPUT V$
910 PAGE
920 PRINT "WOULD YOU LIKE TO REDIGITZE ANY OF THE POINTS?"
930 INPUT Q$
940 IF Q$="N" THEN 1040
950 PRINT "WHICH POINT NO."
960 INPUT I
970 PRINT "DIGITIZE THE POINT"
980 INPUT @8:T(I),Y,Z$
990 T(I)=(T(I)-T0)*T3
1000 GO TO 920
1010 REM*****************************************************************
1020 REM*****STORE DATA ON MAGNETIC TAPE*********************************
1030 REM*****************************************************************
1040 PAGE
1050 PRINT "WOULD YOU LIKE TO STORE THIS TIME-DISTANCE INFO ON TAPE?"
1060 INPUT Q$
1070 IF Q$="N" THEN 1160
```



```
1080 PRINT "WHICH FILE # WOULD YOU LIKE TO STORE DATA ON?"
1090 INPUT F1
1100 FIND F1
1110 WRITE @33:X$
1120 WRITE @33:N
1130 FOR I=1 TO N
1140 WRITE @33:G(I),T(I)
1150 NEXT I
1160 END
```

```
LIS
1 INIT
3 S9=0
4 L9=1.636363
5 L8=1
6 DIM T(50),D(50)
7 REM : TO USE THIS PROGRAM FOR PAPER PLOTS - SET CORNERS ON PLOTTER
8 REM : TO DEFAULT VALUES OF 10" BY 15" - IT IS DESIGNED TO PLOT
9 REM : AN X AXIS OF 7" AND A Y AXIS OF 5" ON PAPER WHICH IS 8"x 10.5"
10 REM : IN SIZE - WHEN MOUNTING PAPER ON PLOTTER SET LEFT EDGE OF
11 REM : PAPER IN LINE WITH THE SCREWS ON THE LEFT HAND SIDE OF THE
12 REM : PLOTTING SURFACE
19 PAGE
20 PRINT "KEY IN THE PROPER # TO PERORM THE INDICATED FUNCTION"
30 PRINT "          1      ENTER DATA"
40 PRINT "          2      CHANGE OR ADD DATA"
50 PRINT "          3      PLOT DATA AND LABEL AXES"
60 PRINT "          4      CHOOSE BETWEEN PAPER OR CRT PLOT"
61 PRINT "          5      DISPLAY DATA"
62 PRINT "          6      SELECT SYMBOL"
69 PRINT "          7      STORE DATA ON TAPE"
70 PRINT "          8      READ DATA FROM TAPE"
71 PRINT "          9      STOP PROGRAM"
80 PRINT "INPUT THE APPROPRIATE NUMBER"
85 DIM T(50),D(50)
90 INPUT M1
95 PRINT @1,17:1,1.636363
100 GO TO M1 OF 130,320,430,520,220,1550,1610,1800,1530
110 DIM T(50),D(50)
120 PAGE
130 PRINT "INPUT TIME DEPTH VALUES, END LIST WITH TIME LESS THAN ZERO"
140 J1=1
150 PRINT "DISTANCE(";J1;") = ";
160 INPUT T(J1)
162 IF T(J1)<0 THEN 210
```



```
170 PRINT "TIME(";J1;") = ";
180 INPUT D(J1)
190 J1=J1+1
200 GO TO 150
210 J1=J1-1
220 PAGE
230 E$="POINT NO."
240 D$="TIME (MSEC)"
250 F$="DEPTH (MSEC)"
260 PRINT E$,F$,D$
270 PRINT
280 PRINT
290 FOR I=1 TO J1
300 PRINT I,T(I),D(I)
310 NEXT I
320 PRINT "WOULD YOU LIKE TO CHANGE OR ADD ANY POINTS (ANSWER Y OR N)??"
330 INPUT Q$
340 IF Q$="Y" THEN 360
350 GO TO 19
360 PRINT "KEY IN THE POINT NO."
370 INPUT I
380 PRINT "KEY IN THE CORRECTED OR ADDED POINT VALUES"
390 INPUT T(I),D(I)
400 IF I<J1 THEN 420
410 J1=I
420 GO TO 220
430 PAGE
440 PRINT "WHAT ARE X AND Y SCALE FACTORS?"
450 INPUT X2,Y2
451 X1=7*X2
452 Y1=5*Y2
460 PRINT "WHAT IS THE X LABEL?"
470 INPUT X$
480 PRINT "WHAT IS THE Y LABEL?"
490 INPUT Y$
```

```
500 PRINT "WHAT IS THE BORING HOLE NUMBER?"
510 INPUT B$
520 PRINT "FOR PAPER PLOT TYPE 1; FOR CRT PLOT TYPE 32"
530 INPUT N0
535 PRINT "WOULD YOU LIKE TO PLOT THE AXIS (ANSWER Y OR N)"
536 INPUT C$
540 PRINT @1,17:1,1.636363
541 PRINT "WOULD YOU LIKE TO PLOT ON GRAPH PAPER (ANSWER Y OR N)"
542 INPUT G$
543 IF G$="N" THEN 550
544 PRINT "MOVE PEN TO ORIGIN AND PRESS CALL BUTTON ON PLOTTER"
545 INPUT @1,27:X3,Y4,G$
546 X4=X3+70
547 Y3=Y4+50
548 GO TO 640
550 X3=18
560 X4=88
570 Y3=61
580 Y4=11
590 GO TO 640
600 X3=45
610 X4=105
620 Y3=85
630 Y4=15
640 PAGE
650 VIEWPORT X3,X4,Y4,Y3
660 WINDOW 0,X1,0,Y1
665 IF C$="N" THEN 680
670 AXIS @N0:X2/2,Y2/2
675 AXIS @N0:X2/2,Y2/2,X1,Y1
680 GOSUB 1390
690 REMARK
700 REMARK TIC LABEL SECTION
705 IF C$="Y" THEN 720
707 GO TO 1331
```



```
710 REMARK
720 FOR I=0 TO X1 STEP X2
730 WINDOW 0,X1,0,Y1
740 MOVE @N0:I,0
750 IF I=0 THEN 790
760 L1=LGT(I)
770 L1=INT(L1+1.0E-3)+1
780 GO TO 800
790 L1=1
800 SCALE 1,1
810 RMOVE @N0:-L1/2*L8-L8,-L9
820 PRINT @N0:I
830 NEXT I
840 WINDOW 0,X1,0,Y1
850 VIEWPORT X3,X4,Y4,Y3
860 MOVE @N0:X1/2,0
870 SCALE 1,1
880 RMOVE @N0:0,5
890 M=LEN(X$)/2
900 RMOVE @N0:-L8*M,-6*L9
910 PRINT @N0:X$
920 FOR J=0 TO Y1 STEP Y2
930 WINDOW 0,X1,0,Y1
940 MOVE @N0:0,J
950 IF J=0 THEN 990
960 L2=LGT(J)
970 L2=INT(L2+1.0E-3)
980 GO TO 1000
990 L2=0
1000 SCALE 1,1
1010 RMOVE @N0:-L8*(L2+3),-0.5*L8
1020 PRINT @N0:J
1030 NEXT J
1040 REMARK
1050 REMARK*****Y AXIS*****
```

```
1060 REMARK
1070 WINDOW 0,X1,0,Y1
1080 MOVE @N0:0,Y1/2
1090 SCALE 1,1
1100 L=LEN(Y$)/2
1110 IF N0=32 THEN 1140
1120 RMOVE @N0:-4*L9,-L
1130 GO TO 1150
1140 RMOVE @N0:-5*L9,L*2
1150 FOR I=1 TO LEN(Y$)
1160 A$=SEG(Y$,I,1)
1170 PRINT @N0,25:90
1180 PRINT @N0:A$;
1190 IF N0=32 THEN 1220
1210 GO TO 1230
1220 RMOVE @N0:0,-2.82
1230 NEXT I
1240 HOME
1250 REMARK
1260 REMARK*********PRINT THE TITLE*****1000 REMARK
1270 WINDOW 0,X1,0,Y1
1280 MOVE @N0:X1/2,Y1
1290 SCALE 1,1
1300 C$=N$
1310 RMOVE @N0:L8*(-LEN(C$)/2),4*L9
1320 PRINT @N0,25:0
1330 PRINT @N0:C$
1331 WINDOW 0,150,0,100
1332 VIEWPORT 0,150,0,100
1333 MOVE @1:X3,Y4
1340 INPUT Z$
1350 GO TO 19
1360 REMARK*********************************************
1370 REMARK PLOT DATA POINTS WITH TRIANGLES
1380 REMARK*********************************************
```



```
1390 WINDOW 0,X1,0,Y1
1400 VIEWPORT X3,X4,Y4,Y3
1410 MOVE @N0:0,0
1420 FOR I=1 TO J1
1430 MOVE @N0:T(I),D(I)
1440 DRAW @N0:T(I),D(I)
1450 S1=X1/70*1.25
1460 S2=Y1/70*1.25
1461 IF S9<>1 AND S9<>2 THEN 1510
1462 IF S9=2 THEN 1502
1470 RMOVE @N0:S1/2,S2/3
1480 RDRAW @N0:-S1/2,-S2
1490 RDRAW @N0:-S1/2,S2
1500 RDRAW @N0:S1,0
1501 GO TO 1510
1502 REM::::::::: PLOT SQUARES :::::::::::::::
1503 RMOVE @N0:S1/2,-S2/2
1504 RDRAW @N0:0,S2
1505 RDRAW @N0:-S1,0
1506 RDRAW @N0:0,-S2
1507 RDRAW @N0:S1,0
1510 NEXT I
1520 RETURN
1530 END
1540 IF N0=32 THEN 1180
1550 PAGE
1560 PRINT "CHOOSE AND KEY IN THE APPROPRIATE SYMBOL NO."
1570 PRINT "      1  FOR TRIANGLE"
1580 PRINT "      2  FOR SQUARE"
1590 INPUT S9
1600 GO TO 19
1610 REM: STORE DATA ON TAPE
1620 PRINT "TYPE IN IDENTIFICATION"
1630 INPUT N$
1640 PRINT "INPUT FILE # THAT YOU WANT DATA STORED ON"
```

```
1650 INPUT F3
1660 FIND F3
1670 WRITE N$
1680 WRITE J1
1690 FOR L=1 TO J1
1700 WRITE T(L),D(L)
1710 NEXT L
1720 GO TO 19
1800 REM: READ DATA FROM TAPE
1810 PRINT "INPUT FILE # DATA IS TO BE READ FROM"
1820 INPUT F3
1825 FIND F3
1830 READ @33:N$
1840 READ @33:J1
1850 FOR L=1 TO J1
1860 READ @33:T(L),D(L)
1870 NEXT L
1880 GO TO 19
```

REFINT 1

```
LIS
90 DIM X(4,2),V(4,2),D(4,2),S1(2),A$(1),V2(4),T(4,2)
100 PRINT "WOULD YOU LIKE TO PROCESS BOTH A FORWARD AND REVERSE LINE?"
110 INPUT A$
120 IF A$="Y" THEN 190
130 F1=1
140 PRINT "IS THE LINE BEING PROCESSED FORWARD OF REVERSE (TYPE F OR R)"
150 INPUT A$
160 IF A$="F" THEN 200
170 F1=3
180 GO TO 200
190 F1=2
200 PRINT "TYPE IN LINE IDENTIFICATION"
210 INPUT B$
220 PRINT "DIGITIZE THE FOLLOWING INFORMATION FROM THE T-D PLOT"
230 PRINT "JJDIGITIZE THE ORIGIN"
240 INPUT @8:A0,B0,M$
250 PRINT "G"
260 PRINT "JDIGITIZE THE RIGHTMOST POINT ON THE HORIZONTAL AXIS"
270 INPUT @8:A2,B2,M$
280 PRINT "G"
290 PRINT "JDIGITIZE THE HIGHEST POINT ON THE VERTICAL AXIS"
300 INPUT @8:A4,B4,M$
310 PRINT "G"
320 REMARK:*******************************************************
330 REMARK:      INITIALIZE VARIABLES
340 REMARK:*******************************************************
350 L1=0
360 L2=0
370 FOR I=1 TO 4
380 FOR J=1 TO 2
390 X(I,J)=0
400 V(I,J)=0
410 T(I,J)=0
420 D(I,J)=0
```

```
430 NEXT J
440 NEXT I
450 IF F1=3 THEN 490
460 PRINT "HOW MANY LAYERS ARE ASSOCIATED WITH THE FORWARD LINE?"
470 INPUT L1
480 IF F1=1 THEN 520
490 PRINT "JHOW MANY LAYERS ARE ASSOCIATED WITH THE REVERSE LINE?"
500 INPUT L2
510 IF F1=3 THEN 630
520 PRINT "JDIGITIZE CRITICAL DISTANCES ON THE FORWARD LINE"
530 FOR I=1 TO L1
540 IF I=L1 THEN 570
550 PRINT "JDIGITIZE CRITICAL DISTANCE #";I
560 GO TO 580
570 PRINT "JDIGITIZE ANY POINT ON THE HIGHEST FORWARD VELOCITY LINE"
580 INPUT @8:X(I,1),T(I,1),M$
590 PRINT "G"
600 NEXT I
610 IF F1=1 THEN 720
620 PAGE
630 PRINT "DIGITIZE CRITICAL DISTANCES ON REVERSE LINE:"
640 FOR I=1 TO L2
650 IF I=L2 THEN 680
660 PRINT "JCRITICAL DISTANCE #";I
670 GO TO 690
680 PRINT "JDIGITIZE ANY POINT ON THE HIGHEST REVERSE VELOCITY LINE"
690 INPUT @8:X(I,2),T(I,2),M$
700 PRINT "G"
710 NEXT I
720 PAGE
730 IF F1=3 THEN 780
740 PRINT "FROM THE KEYBOARD ENTER THE FOLLOWING INFORMATION:"
750 PRINT "JJDISTANCE OF FORWARD SHOTPOINT FROM ORIGIN"
760 INPUT S1(1)
770 IF F1=1 THEN 810
```



```
780 PRINT "JDISTANCE OF REVERSE SHOTPOINT FROM THE ORIGIN"
790 INPUT S1(2)
800 IF F1=3 THEN 840
810 PRINT "INPUT THE FORWARD SHOTHOLE DEPTH"
820 INPUT D8
830 IF F1=1 THEN 860
840 PRINT "INPUT THE REVERSE SHOTHOLE DEPTH"
850 INPUT D9
860 A1=0
870 B1=0
880 PRINT "JTHE MAXIMUM VALUE OF THE HORIZONTAL AXIS"
890 INPUT A3
900 PRINT "JTHE MAXIMUM VALUE ON THE VERTICAL AXIS"
910 INPUT B5
920 A=A2-A0
930 B=B4-B0
940 REMARK*****************************************************
950 REMARK: FORWARD CALCULATIONS MADE IN THE NEXT SECTION
960 REMARK*****************************************************
970 IF F1=3 THEN 1060
980 FOR I=1 TO L1
990 X(I,1)=(X(I,1)-A0)/A*(A3-A1)
1000 T(I,1)=(T(I,1)-B0)/B*(B5-B1)
1010 X(I,1)=ABS(X(I,1)-S1(1))
1020 NEXT I
1030 REMARK:****************************************************
1040 REMARK: CALCULATIONS FOR REVERSE LINE
1050 REMARK:****************************************************
1060 IF F1=1 THEN 1150
1070 FOR I=1 TO L2
1080 X(I,2)=(X(I,2)-A0)/A*(A3-A1)
1090 T(I,2)=(T(I,2)-B0)/B*(B5-B1)
1100 X(I,2)=ABS(X(I,2)-S1(2))
1110 NEXT I
1120 REMARK:****************************************************
```

AD-A121 196 ANALYTICAL AND DATA PROCESSING TECHNIQUES FOR INTERPRETATION OF GEOPHYSIC..(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS GEOTE.. 3/4

UNCLASSIFIED D K BUTLER ET AL. SEP 82 WES/MP/GL-82-16 F/G 8/7 NL

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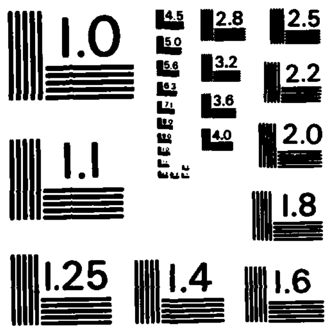

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

```
1130 REMARK:  COMPUTE VELOCITIES
1140 REMARK:***************************************************
1150 FOR I=1 TO 2
1160 IF F1=3 AND I=1 OR (F1=1 AND I=2) THEN 1180
1170 V(1,I)=(X(1,I)-A1)/(T(1,I)-B1)*1000
1180 NEXT I
1190 IF F1=3 THEN 1240
1200 FOR I=2 TO L1
1210 V(I,1)=(X(I,1)-X(I-1,1))/(T(I,1)-T(I-1,1))*1000
1220 NEXT I
1230 IF F1=1 THEN 1280
1240 FOR I=2 TO L2
1250 V(I,2)=(X(I,2)-X(I-1,2))/(T(I,2)-T(I-1,2))*1000
1260 NEXT I
1270 REMARK:*******************************************************
1280 REMARK:         COMPUTE DEPTHS
1290 REMARK:*******************************************************
1300 IF F1=3 THEN 1380
1310 D(1,1)=X(1,1)/2*SQR((V(2,1)-V(1,1))/(V(2,1)+V(1,1)))+D8/2
1320 IF L1=2 THEN 1370
1330 D(2,1)=5/6*D(1,1)+X(2,1)/2*SQR((V(3,1)-V(2,1))/(V(3,1)+V(2,1)))
1340 IF L1=3 THEN 1370
1350 D1=1/6*D(1,1)+3/4*D(2,1)
1360 D(3,1)=D1+X(3,1)/2*SQR((V(4,1)-V(3,1))/(V(4,1)+V(3,1)))
1370 IF F1=1 THEN 1440
1380 D(1,2)=X(1,2)/2*SQR((V(2,2)-V(1,2))/(V(2,2)+V(1,2)))+D9/2
1390 IF L2=2 THEN 1440
1400 D(2,2)=5/6*D(1,2)+X(2,2)/2*SQR((V(3,2)-V(2,2))/(V(3,2)+V(2,2)))
1410 IF L2=3 THEN 1440
1420 D2=1/6*D(1,1)+3/4*D(2,2)
1430 D(3,2)=D2+X(3,2)/2*SQR((V(4,2)-V(3,2))/(V(4,2)+V(3,2)))
1440 REMARK*******************************************************
1450 REMARK:     OUTPUT SECTION RESULTS ARE NOW COMPLETE
1460 REMARK*******************************************************
1470 IF L1<>L2 OR F1=1 OR F1=3 THEN 1540
```



```
1480 REMARK*******************************************************
1490 REMARK:         COMPUTE TRUE VELOCITIES
1500 REMARK:******************************************************
1510 FOR I=1 TO L1
1520 V2(I)=2*V(I,1)*V(I,2)/(V(I,1)+V(I,2))
1530 NEXT I
1540 PAGE
1550 PRINT B$
1560 PRINT "J"
1570 PRINT "           FORWARD                          REVERSE"
1580 PRINT USING 1590:
1590 IMAGE 11X,"_______",25X,"_______"
1600 PRINT "J"
1610 PRINT USING 1620:
1620 IMAGE 22X,"THE CRITICAL DISTANCES ARE:"
1630 PRINT "J"
1640 L=L1
1650 IF L1>L2 THEN 1670
1660 L=L2
1670 FOR I=1 TO L-1
1680 PRINT USING 1690:I,X(I,1),I,X(I,2)
1690 IMAGE 11X,"X(",1D,") =",6D,18X,"X(",1D,") =",6D
1700 NEXT I
1710 PRINT "J"
1720 PRINT USING 1730:
1730 IMAGE 22X,"THE APPARENT VELOCITIES ARE:"
1740 FOR I=1 TO L
1750 PRINT USING 1760:I,V(I,1),I,V(I,2)
1760 IMAGE 11X,"V(",1D,") =",6D," fps",17X,"V(",1D,") =",6D," fps"
1770 NEXT I
1780 PRINT "J"
1790 PRINT USING 1800:
1800 IMAGE 11X,"THE CALCULATED DEPTHS ARE:"
1810 PRINT "J"
1820 FOR I=1 TO L-1
```

```
1830 PRINT USING 1840:I,D(I,1),I,D(I,2)
1840 IMAGE 11X,"D(",1D,") =",3D.2D  ," ft",18X,"D(",1D,") =",3D.2D," ft"
1850 NEXT I
1860 IF L1<>L2 OR F1=1 OR F1=3 THEN 1960
1870 PRINT "J"
1880 PRINT USING 1890:
1890 IMAGE 22X,"THE TRUE VELOCITIES ARE:"
1900 PRINT "J"
1910 FOR I=1 TO L
1920 PRINT USING 1930:I,V2(I)
1930 IMAGE 11X,"V(",1D,") =",6D
1940 NEXT I
1950 GO TO 1970
1960 PRINT "JJTHE TRUE VELOCITIES WERE NOT COMPUTED FOR THIS CASE"
1970 END

+
```

DOMER 1

```
LIST
10 INIT
15 REM DOMER(DIGITIZATION OF MULTI-EVENT REFRACTION DATA)-DEY
16 REM PROGRAM WILL DIGITIZE PEAK ARRIVAL TIME AND 1 CYCLE OF
17 REM EACH EVENT. IT WILL HANDLE UP TO 5 EVENTS PER TRACE FOR 24
18 REM TRACES. CALCULATES FREQ&GROUP VELOCITY AND OUTPUTS IN TABLE
19 REM GEOPHONES MUST BE EQUALLY SPACED. T/D PLOT OF PK FOR ALL EVENTS.
20 DIM T1(24),T2(24),T3(24),T4(24),T5(24),D(24)
30 DIM F1(24),F2(24),F3(24),F4(24),F5(24),H1(24),H2(24)
35 S9=0
37 F9=0
40 T1=-1
45 T2=-1
50 T3=-1
55 T4=-1
60 T5=-1
65 F1=T1
70 F2=T2
75 F3=T3
80 F4=T4
90 F5=T5
110 PRINT "ENTER TITLE"
120 INPUT T$
130 PRINT "ENTER GEOPHONE SPACING"
140 INPUT X
150 PRINT "ENTER TIME INTERVAL TO BE DIGITIZED"
160 INPUT R
170 PRINT "DIGITIZE TIME INTERVAL"
180 INPUT @8:T8,Z,Z$
190 PRINT "G"
200 INPUT @8:T9,Z,Z$
210 PRINT "G"
220 S6=R/(T9-T8)
225 PRINT "DIGITIZE ZERO TIME"
227 INPUT @8:T7,Z,Z$
```

```
228 PRINT "G"
230 PRINT "ENTER NUMBER OF EVENTS TO BE DIGITIZED"
240 INPUT N
250 FOR M=1 TO N
260 PRINT "ENTER STARTING TRACE NUMBER"
270 INPUT C
280 FOR K=C TO 24
290 PRINT "DIGITIZE EVENT#";M;" TRACE ";K;" PEAK"
300 INPUT @8:T,Z,Z$
305 T=(T-T7)*S6
310 GOSUB 900
320 PRINT "DIGITIZE EVENT#";M;" TRACE ";K;" LEFT TROUGH"
330 INPUT @8:L,Z,Z$
340 GOSUB 900
350 PRINT "DIGITIZE EVENT#";M;" TRACE ";K;" RIGHT TROUGH"
360 INPUT @8:R,Z,Z$
370 GOSUB 900
380 P=1/((R-L)*S6)
385 P=INT(P*10000)/10
390 GOSUB 600
400 NEXT K
410 NEXT M
420 REM:::OUTPUT DATA
430 M=1
440 H1=T1
450 H2=F1
460 GOSUB 800
470 M=M+1
480 IF M>N THEN 590
490 H1=T2
500 H2=F2
510 GOSUB 800
520 M=M+1
530 IF M>N THEN 590
540 H1=T3
```



```
550 H2=F3
560 GOSUB 800
570 IF M>N THEN 590
572 H1=T4
574 H2=F4
576 GOSUB 800
579 M=M+1
580 IF M>N THEN 590
582 H1=T5
584 H2=F5
586 GOSUB 800
590 PRINT "ALL EVENTS PRINTED  **NORMAL TERMINATION***"
595 GO TO 4000
600 REM:::SUBR DATA ARRAY SORT:::
610 GO TO M OF 630,660,690,720,750
620 PRINT "SORT ERROR"
630 T1(K)=T
640 F1(K)=P
650 RETURN
660 T2(K)=T
670 F2(K)=P
680 RETURN
690 T3(K)=T
700 F3(K)=P
710 RETURN
720 T4(K)=T
730 F4(K)=P
740 RETURN
750 T5(K)=T
760 F5(K)=P
770 RETURN
800 REM::::SUBR OUTPUT DATA TABLE::::
805 PRINT "        ";T$
806 PRINT " "
810 PRINT "EVENT NUMBER ";M
```

```
812 PRINT
815 PRINT "  X,ft                 T,msec           F,hz               Vg,ft/s"
820 PRINT "---------------------------------------------------------------------"
825 FOR K=1 TO 24
830 S=K*X
835 IF H1(K)=-1 THEN 860
836 H1(K)=INT(H1(K)*10)/10
840 V=S/H1(K)
842 V=INT(V*10000)/10
845 PRINT S,H1(K),H2(K),V
850 GO TO 870
860 PRINT S
870 NEXT K
875 COPY
880 PAGE
885 GOSUB 2000
890 RETURN
900 REM:::SUBR FLAG SORT::
910 PRINT "G"
915 PAGE
920 IF Z$="4" THEN 290
930 IF Z$="8" THEN 400
940 IF Z$="2" THEN 410
950 RETURN
1000 STOP
2000 REM:::SUBR PLOT::
2010 L9=1.63636
2020 L8=1
2040 REM TO USE THIS PROGRAM FOR PAPER PLOTS - SET CORNERS ON PLOTTER
2050 REM:TO DEFAULT VALUES OF 10" BY 15" - IT IS DESIGNED TO PLOT
2060 REM:AN X AXIS OF 7" AND A Y AXIS OF 5" ON PAPER WHICH IS 8"x 10.5"
2070 REM: IN SIZE - WHEN MOUNTING PAPER ON PLOTTER SET LEFT EDGE OF
```



```
2130 PAGE
2135 IF F9=1 THEN 2210
2140 PRINT "WHAT ARE X AND Y SCALE FACTORS?"
2150 INPUT X2,Y2
2160 X1=7*X2
2170 Y1=5*Y2
2180 X$="DISTANCE,ft."
2190 Y$="TIME,msec."
2200 N0=1
2210 GOSUB 3405
2230 PRINT @1,17:1,1.636363
2240 X3=18
2250 X4=88
2260 Y3=61
2270 Y4=11
2330 PAGE
2340 VIEWPORT X3,X4,Y4,Y3
2350 WINDOW 0,X1,0,Y1
2360 IF F9=1 THEN 3140
2370 AXIS @N0:X2/2,Y2/2
2380 AXIS @N0:X2/2,Y2/2,X1,Y1
2400 REMARK
2410 REMARK TIC LABEL SECTION
2440 REMARK
2450 FOR I=0 TO X1 STEP X2
2460 WINDOW 0,X1,0,Y1
2470 MOVE @N0:I,0
2480 IF I=0 THEN 2520
2490 L1=LGT(I)
2500 L1=INT(L1+1.0E-3)+1
2510 GO TO 2530
2520 L1=1
2530 SCALE 1,1
2540 RMOVE @N0:-L1/2*L8-L8,-L9
2550 PRINT @N0:I
```

```
2560 NEXT I
2570 WINDOW 0,X1,0,Y1
2580 VIEWPORT X3,X4,Y4,Y3
2590 MOVE @N0:X1/2,0
2600 SCALE 1,1
2610 RMOVE @N0:0,5
2620 M9=LEN(X$)/2
2630 RMOVE @N0:-L8*M9,-6*L9
2640 PRINT @N0:X$
2650 FOR J=0 TO Y1 STEP Y2
2660 WINDOW 0,X1,0,Y1
2670 MOVE @N0:0,J
2680 IF J=0 THEN 2720
2690 L2=LGT(J)
2700 L2=INT(L2+1.0E-3)
2710 GO TO 2730
2720 L2=0
2730 SCALE 1,1
2740 RMOVE @N0:-L8*(L2+3),-0.5*L8
2750 PRINT @N0:J
2760 NEXT J
2770 REMARK
2780 REMARK*****Y AXIS*****
2790 REMARK
2800 WINDOW 0,X1,0,Y1
2810 MOVE @N0:0,Y1/2
2820 SCALE 1,1
2830 L=LEN(Y$)/2
2850 RMOVE @N0:-4*L9,-L
2880 FOR I=1 TO LEN(Y$)
2890 A$=SEG(Y$,I,1)
2900 PRINT @N0,25:90
2910 PRINT @N0:A$;
2950 NEXT I
2960 HOME
```



```
2970 REMARK
2980 REMARK*********PRINT THE TITLE*****1000 REMARK
2990 WINDOW 0,X1,0,Y1
3000 MOVE @N0:X1/2,Y1
3010 SCALE 1,1
3020 C$=T$
3030 RMOVE @N0:L8*(-LEN(C$)/2),4*L9
3040 PRINT @N0,25:0
3050 PRINT @N0:C$
3060 WINDOW 0,150,0,100
3070 VIEWPORT 0,150,0,100
3080 MOVE @1:X3,Y4
3090 REM::?INPUT Z$??
3095 F9=1
3110 REMARK********************************************
3120 REMARK PLOT DATA POINTS WITH TRIANGLES
3130 REMARK********************************************
3140 WINDOW 0,X1,0,Y1
3150 VIEWPORT X3,X4,Y4,Y3
3160 MOVE @N0:0,0
3170 FOR I=1 TO 24
3180 D(I)=I*10
3185 IF H1(I)<0 THEN 3360
3190 MOVE @N0:D(I),H1(I)
3200 DRAW @N0:D(I),H1(I)
3210 S1=X1/70*1.25
3220 S2=Y1/70*1.25
3230 IF S9<>1 AND S9<>2 THEN 3360
3240 IF S9=2 THEN 3300
3250 RMOVE @N0:S1/2,S2/3
3260 RDRAW @N0:-S1/2,-S2
3270 RDRAW @N0:-S1/2,S2
3280 RDRAW @N0:S1,0
3290 GO TO 3360
3300 REM::::::::: PLOT SQUARES ::::::::::::::::
```

```
3310 RMOVE @N0:S1/2,-S2/2
3320 RDRAW @N0:0,S2
3330 RDRAW @N0:-S1,0
3340 RDRAW @N0:0,-S2
3350 RDRAW @N0:S1,0
3360 NEXT I
3370 RETURN
3380 END
3390 REM
3400 PAGE
3405 REM::: SUBR CHOOSE PLOTTING SYMBOL::::
3410 PRINT "CHOOSE AND KEY IN THE APPROPRIATE SYMBOL NO."
3420 PRINT "      1  FOR TRIANGLE"
3430 PRINT "      2  FOR SQUARE"
3432 INPUT S9
3435 PRINT "CHANGE PEN COLOR IF DESIRED AND PRESS RETURN"
3436 INPUT Z$
3550 RETURN
4000 END
```

APPENDIX I: REFRDIR EXAMPLE AND LISTING

The following computational procedure is used by REFRDIR to determine the phase velocities, $v_n^{\pm}$, and intercept times, $t_{o,n}^{\pm}$, for the direct and reversed refraction profiles (+ and - for the direct and reversed profiles, respectively) for four layers (n=1,2,3,4) or three interfaces (n=2,3,4). The given data are (see Figure 60): 1) the layer velocities, α_n, 2) the interface dips, δ_n, and 3) the layer thicknesses, $H_n^{\pm}$. The last layer, n=4, is a semi-infinite half space. The top interface n=1, is the air/ground interface and it is assumed to be horizontal. The angle between the interfaces of layer n is ψ_n: $\psi_n = \delta_{n+1} - \delta_n$.

The phase velocites and the intercept times for the first interface (n=1 or top surface) are $v_1^{\pm} = \alpha_1$, $t_{o1}^{\pm} = 0$.

For interface #2, (n=2), we compute:

$$\sin\theta_{12} = \alpha_1/\alpha_2; \quad \cos\theta_{12} = (1 - \sin^2\theta_{12})^{1/2}$$

then

$$v_2^{\pm} = \alpha_1/(\sin\theta_{12}\cos\psi_1 \mp \cos\theta_{12}\sin\psi_1)$$

$$t_{o2}^{\pm} = (2H_1^{\pm}/\alpha_1)\cos\theta_{12}.$$

For interface #3 (n=3), we compute:

$$\sin\theta_{23} = \alpha_2/\alpha_3\ ; \quad \cos\theta_{23} = (1 - \sin^2\theta_{23})^{1/2}$$

$$\sin\theta_{13}^{\pm} = (\alpha_1/\alpha_2)(\sin\theta_{23}\cos\psi_2 \pm \cos\theta_{23}\sin\psi_2)$$

$$\cos\theta_{13}^{\pm} = (1 - \sin^2\theta_{13}^{\pm})^{1/2}$$

then

$$v_3^{\pm} = \alpha_1/(\sin\theta_{13}^{\pm}\cos\psi_1 \mp \cos\theta_{13}^{\pm}\sin\psi_1)$$

$$t_{o3}^{\pm} = (2H_2^{\pm}/\alpha_2)\cos\theta_{23} + (H_1^{\pm}/\alpha_1)(\cos\theta_{13}^{+} + \cos\theta_{13}^{-}).$$

Finally, for interface #4, we compute:

$$\sin\theta_{34} = \alpha_3/\alpha_4; \quad \cos\theta_{34} = (1 - \sin^2\theta_{34})^{1/2}$$

$$\sin\theta_{24}^{\pm} = (\alpha_2/\alpha_3)(\sin\theta_{34}\cos\psi_3 \pm \cos\theta_{34}\sin\psi_3)$$

$$\cos\theta_{24}^{\pm} = (1 - \sin^2\theta_{24}^{\pm})^{1/2}$$

$$\sin\theta_{14}^{\pm} = (\alpha_1/\alpha_2)(\sin\theta_{24}^{\pm}\cos\psi_2 \pm \cos\theta_{24}^{\pm}\sin\psi_2)$$

$$\cos\theta_{14}^{\pm} = (1 - \sin^2\theta_{14}^{\pm})^{1/2}$$

and then finally,

$$v_4^{\pm} = \alpha_1/(\sin\theta_{14}^{\pm}\cos\psi_1 \mp \cos\theta_{14}^{\pm}\sin\psi_1)$$

$$t_{o4}^{\pm} = (2H_3^{\pm}/\alpha_3)\cos\theta_{34} + (H_2^{\pm}/\alpha_2)(\cos\theta_{24}^{+} + \cos\theta_{24}^{-}) + (H_1^{\pm}/\alpha_1)(\cos\theta_{14}^{+} + \cos\theta_{14}^{-}).$$

Note, the computations of $t_{on}^{\pm}$ are made as a running sum; each term is computed as the values of the $\cos\theta_{in}^{\pm}$ are computed.

The equation relating the layer "thicknesses" of the reversed profile, H_n^-, to those of the direct profile, H_n^+, is:

$$H_n^- = H_n^+ - L\sin\psi_n \prod_{i=0}^{n-1} \cos\psi_i$$

where the symbol $\prod$ represents a product; that is

$$\prod_{i=0}^{2} \cos\psi_i = \cos\psi_o \cos\psi_1 \cos\psi_2$$

(recall $\psi_o = 0$ and, therefore, $\cos\psi_o = 1$).

```
**FRN*,R0S0441/PLOTS,E
C                     REFRAC 1                  (A.F. GANGI/W. DILLON)
C
C      PROGRAM REFRAC 1 IS A MODELLING PROGRAM WHOSE INPUT DATA ARE:
C          1). THE NUMBER OF LAYERS . . . . . . .(NLAYRS)
C          2). THE VELOCITY IN EACH LAYER . . .(ALPHA(N))
C          3). THE DIP OF THE LAYER INTERFACES IN DEGREES . .
C              . . . . . . . . . . . . . . . . .(DELTA(N))
C      AND 4).THE LAYER THICKNESSES . . . . . .(HPLUS(N),HMINUS(N))
C
C        NOTE: N VARIES FROM 1 TO NLAYRS (1.LE.N.LE.NLAYRS) FOR
C     ALPHA(N) AND DELTA(N), BUT 1.LE.N.LE.(NLAYRS-1) FOR HPLUS(N)
C     AND HMINUS(N).
C
C            *****  SEE THE DIAGRAM IN FIGURE 1  *****
C
C     ALPHA(1), HPLUS(1) & HMINUS(1) ARE THE VELOCITY & LAYER
C     THICKNESSES OF THE FIRST LAYER WHILE DELTA(1) IS THE DIP
C     ANGLE OF ITS TOP SURFACE (THE GROUND SURFACE)
C
C         THE PROGRAM COMPUTES AND PRINTS OUT, FOR BOTH DIRECT AND
C     REVERSED PROFILES:
C         1). THE HORIZONTAL PHASE VELOCITIES  . .(VPLUS(N),VMINUS(N))
C     AND  2). THE INTERCEPT TIMES . . . . . . . . (TPLUS(N),TMINUS(N))
C     FOR EACH REFRACTION.  (2.LE.N.LE.NLAYRS)
C
C        ***  DEFINITIONS AND LIST OF VARIABLES  ***
C
C     ALPNM1 = (ALPHA N MINUS 1) = (N-1)ST LAYER'S VELOCITY WHICH IS
C         COMPARED WITH THE VELOCITY IN LAYER N, ALPHA(N), TO INSURE
C         THE VELOCITIES ARE MONOTONICALLY DECREASING.
C
C     ALPHA(N) = VELOCITY IN LAYER N.  (1.LE.N.LE.NLAYRS)
C
C     COSPSI = (COSINE PSI) = COSINE OF THE ANGLE BETWEEN LAYER N'S
C         INTERFACES, PSI(N).  (1.LE.N.LE.NLAYRS-1)
C
C     COSP1 = (COSINE PSI(1)) = COSINE OF THE ANGLE BETWEEN THE
C         FIRST LAYER'S SURFACES.
C
C     CTMIN = (COSINE THETAM(I,N)) = COSINE OF THE ANGLE BETWEEN THE
C         ITH-INTERFACE NORMAL AND THE RAY WHICH REFRACTS ALONG THE NTH
C         INTERFACE (N>1).  THIS IS FOR UPWARD TRAVELLING WAVES.  (SEE
C         FIGURE 1 AND THETAM(I,N)).
C
C     CTPIN = (COSINE THETAP(I,N)) = SAME AS CTMIN EXCEPT FOR THE
C         DOWNWARD TRAVELLING WAVES.
C
C     DELTA(N) = THE DIP ANGLE (IN DEGREES) OF THE NTH INTERFACE, THE
C         TOP SURFACE OF LAYER N.  (DELTA(1) = TOP SURFACE DIP ANGLE =
C         ZERO DEGREES).   (1.LE.N.LENLAYRS)
C
C     HMINUS(N) = THE THICKNESS OF THE NTH LAYER FOR THE REVERSED
C         PROFILE  (SEE FIGURE 1).  (1.LE.N.LE.NLAYRS-1)
C
```

```
C   HPLUS(N) = THE SAME AS HMINUS(N) EXCEPT FOR THE DIRECT PROFILE
C
C   NLAYRS = (NUMBER OF LAYERS) = NUMBER OF LAYERS FOR WHICH
C        VELOCITIES ARE GIVEN.  (THE LAST LAYER IS A HALF SPACE)
C
C   NX2LST = NEXT TO LAST) = NLAYRS - 1
C
C   P = 0.0174532925 = PI/180 = CONVERSION FACTOR, DEGREES TO RADIANS
C
C   PSI(N) = ANGLE (IN RADIANS) BETWEEN THE SURFACES OF THE NTH
C        LAYER = P*(DELTA(N+1) - DELTA(N)).  (1.LE.N.LE.NLAYRS-1)
C
C   SINPSI = THE SINE OF PSI(N), (SEE COSPSI, PSI(N))
C
C   SINP1 = (SINE OF PSI(1)),  (SEE COSP1)
C
C   STMIN = (SINE THETAM(I,N)) = SINE OF THETA MINUS (SEE CTMIN)
C
C   STPIN = (SINE THETAP(I,N)) = SINE OF THETA PLUS (SEE CTPIN)
C
C   THETAM(I,N) = (THETA MINUS) = ANGLE BETWEEN THE ITH-INTERFACE NOR-
C     MAL AND THE RAY OF THE WAVE THAT REFRACTS ALONG THE NTH INTER-
C     FACE (N>1).  THIS IS FOR UPWARD TRAVELLING RAYS.  (SEE FIG. 1)
C
C   THETAP(I,N) = (THETA PLUS) = SAME AS THETAM EXCEPT THIS IS FOR
C        DOWNWARD TRAVELLING RAYS.  (SEE FIGURE 1)
C
C   TMINUS(N) = INTERCEPT TIME FOR THE WAVE REFRACTED FROM THE NTH
C        INTERFACE FOR THE REVERSED PROFILE.  (2.LE.N.LE.NLAYRS)
C
C   TPLUS(N) = INTERCEPT TIME FOR THE WAVE REFRACTED FROM THE NTH
C        INTERFACE FOR THE DIRECT PROFILE.  (2.LE.N.LE.NLAYRS)
C
C   TMINUN = THE RUNNING SUM FOR TMINUS(N)
C
C   TPLUSN = THE RUNNING SUM FOR TPLUS(N)
C
C   VMINUS(N) = HORIZONTAL PHASE VELOCITY OF THE REFRACTION FROM
C        THE NTH LAYER FOR THE REVERSED PROFILE.  (2.LE.N.LE.NLAYRS)
C
C   VPLUS(N) = HORIZONTAL PHASE VELOCITY OF THE REFRACTION FROM
C        THE NTH LAYER FOR THE DIRECT PROFILE.  (2.LE.N.LE.NLAYRS)
C
C   VRATIO = ALPHA(I)/ALPHA(I+1) = VELOCITY RATIO
C
C             *****  EQUATIONS USED BY REFRAC 1  *****
C
C    1.  SIN(THETA(N-1,N) = ALPHA(N-1)/ALPHA(N)
C
C    2.  SIN(THETAP(I-1,N) = (ALPHA(I-1)/ALPHA(I)) *
C              (SIN(THETAP(I,N) + PSI(I))
C
C    3.  SIN(THETAM(I-1,N) = (ALPHA(I-1)/ALPHA(I)) *
C              (SIN(THETAM(I,N) - PSI(I))
C
```

```
C  4.  VMINUS(N) = ALPHA(1)/SIN(THETAP(1,N) + PSI(1))
C
C  5.  VPLUS(N) = ALPHA(1)/SIN(THETAM(1,N) - PSI(1))
C
C  6.  TPLUS(0,N) = SUM (OVER I=1 TO I=N-1) OF
C           HPLUS(I)*(COS(THETAP(I,N)) + COS(THETAM(I,N)))/ALPHA(I)
C
C  7.  TMINUS(0,N) = SUM (OVER I=1 TO I=N-1) OF
C           HMINUS(I)*(COS(THETAP(I,N)) + COS(THETAM(I,N)))/ALPHA(I)
C
C
C *******************************************************************
C
C      ***  BEGIN PROGRAM REFRAC 1  ***
C
C
        P=0.0174532925
C  DIMENSION INPUT DATA ARRAYS AND COMPUTED ARRAY
      REAL ALPHA(50),ALPA(50),DELTA(50),HPLUS(50),HMINUS(50),  PSI(50)
C
C  DIMENSION AND INITIALIZE OUTPUT DATA ARRAYS
      REAL TPLUS(50),TMINUS(50),VPLUS(50),VMINUS(50)
          DATA TPLUS,TMINUS,VPLUS,VMINUS/200*0.0/
       REAL X(50),Y(50),SPRDLN,SUMCOS,SIGH
       INTEGER D
C
C  READ INPUT DATA: NUMBER OF LAYERS (NLAYRS), LAYER VELOCITIES (AL-
C   PHA), DIP ANGLES (DELTA) AND LAYER THICKNESSES(HPLUS)
       PRINT 7000
 7000 FORMAT(1H1,4X,'INPUT NUMBER OF LAYERS IN MODEL',/)
      READ 1000,NLAYRS
 1000 FORMAT(V)
C
       PRINT 7200
 7200 FORMAT(1H1,4X,'INPUT LENGTH OF SHOT SPREAD',/)
       READ 1000,SPRDLN
       PRINT 7100
 7100 FORMAT(1H1,4X,'FOR EACH LAYER INPUT A LINE ENTRY WITH THE
     & FOLLOWING DATA',/,4X,'SEPARATED BY COMMAS: LAYER VELOCITY,
     &DIP OF INTERFACE,',/,4X,'LAYER THICKNESS',//)
         ALPNM1=0.
      DO 10 N=1,NLAYRS
       READ 1000,ALPHA(N),DELTA(N),HPLUS(N)
       ALPA(N)=ALPHA(N)
       ALPHA(N)=ALPHA(N)/1000
C
C     THE FOLLOWING CHECKS FOR MONOTONICALLY INCREASING VELOCI-
C  TIES, IF THEY DECREASE, PROGRAM PRINTS ERROR MESSAGE & STOPS.
C
         IF (ALPHA(N).LT.ALPNM1) GOTO 900
         ALPNM1 = ALPHA(N)
   10   CONTINUE
      DO 12 N=1,NLAYRS-1
      L=N
      CALL CHMINUS(HPLUS,SPRDLN,L,P,DELTA,HMINUS)
```

```
   12 CONTINUE
C
C PRINT OUT THE DATA READ IN ABOVE TO CHECK FOR ACCURACY
      PRINT 9000,NLAYRS
 9000    FORMAT(1H1,4X,'VELOCITIES ARE IN METERS/SEC',
     &         ' (OR FT/SEC), TIMES ARE IN',/,
     &    5X,'MILLISECS AND LAYER THICKNESSES ARE IN METERS,(FT)',//,
     &    5X,'THERE ARE ',I2,' LAYERS IN THIS MODEL',//,
     &    5X,'LAYER NO.    VELOCITY     DIP (DEGREES)    H+',9X,'H-')
C
      NX2LST=NLAYRS-1
C
      DO 20 N=1,NX2LST
         PRINT 9100,N,ALPA(N),DELTA(N),HPLUS(N),HMINUS(N)
 9100       FORMAT (1H0,7X,I2,6X,F7.0,3X,3F11.1)
C  CALCULATE AND CONVERT LAYER ANGLES, PSI (IN RADIANS), FROM THE
C  DIP ANGLES, DELTA (IN DEGREES)
         PSI(N) = P*(DELTA(N+1) - DELTA(N))
   20 CONTINUE
      PRINT 9200,NLAYRS,ALPA(NLAYRS),DELTA(NLAYRS)
 9200    FORMAT (1H0,7X,I2,6X,F7.0,3X,F11.1)
C
C    DO LOOP 50 PERFORMS THE COMPUTATION OF TPLUS(N), TMINUS(N),
C  VPLUS(N) & VMINUS(N) (2.LE.N.LE.NLAYRS), TPLUS(1)=TMINUS(1)=0.0
C  AND VPLUS(1) = VMINUS(1) = ALPHA(1).
C
            SINP1 = SIN(PSI(1))
            COSP1 = SQRT(1.0 - SINP1*SINP1)
      DO 50 N=2,NLAYRS
C
C    THE COMPUTATION IS STARTED BY FINDING SIN(THETA(N-1,N)) (OR
C  STPIN) USING EQUATION 1.  THE COSINE (CTPIN) IS COMPUTED FROM
C  THE SINE.  STPIN & CTPIN ARE SET EQUAL TO STMIN & CTMIN, RES-
C  PECTIVELY, BECAUSE THETAP(N-1,N) = THETAM(N-1,N).
      STPIN = ALPHA(N-1)/ALPHA(N)
      CTPIN = SQRT(1.0 - STPIN*STPIN)
         STMIN = STPIN
         CTMIN = CTPIN
C
C       THE RUNNING SUMS FOR TPLUS AND TMINUS ARE INITIALIZED TO THE
C  LAST TERMS IN EQUATIONS 6 & 7.
C
         TEMP = 2.0*CTPIN/ALPHA(N-1)
      TPLUSN = HPLUS(N-1)*TEMP
      TMINUN = HMINUS(N-1)*TEMP
C
C    IF N=2 (CORRESPONDING TO THE FIRST REFRACTED WAVE FROM THE
C  SECOND INTERFACE), THE SUMS FOR TPLUS & TMINUS HAVE JUST THE
C  ABOVE TERMS AND THE PROGRAM JUMPS TO LINE 40 TO COMPUTE
C  VPLUS AND VMINUS.
C
        IF (N.EQ.2) GOTO 40
C
C    DO LOOP 30 COMPUTES THE REMAINING TERMS OF TPLUS & TMINUS (THE
C  SUMS IN EQUATIONS 6 & 7).
```

```
C
          DO 30 M=3,N
             I = N-M+1
             PSI1 = PSI(I+1)
             SINPSI = SIN(PSI1)
             COSPSI = SQRT(1.0 - SINPSI*SINPSI)
             VRATIO = ALPHA(I)/ALPHA(I+1)
C
C     IN COMPUTING TPLUS & TMINUS, THE SINES AND COSINES OF THE
C   THETAS FROM THETA(N-1,N) TO THETA(1,N) ARE NEEDED.  THESE ARE
C   COMPUTED USING EQUATIONS 2 & 3.
C
             STPIN = VRATIO*(STPIN*COSPSI + CTPIN*SINPSI)
             STMIN = VRATIO*(STMIN*COSPSI - CTMIN*SINPSI)
               CTPIN = SQRT(1.0 - STPIN*STPIN)
               CTMIN = SQRT(1.0 - STMIN*STMIN)
                 TEMP = (CTPIN + CTMIN)/ALPHA(I)
             TPLUSN = TPLUSN + HPLUS(I)*TEMP
             TMINUN = TMINUN + HMINUS(I)*TEMP
    30    CONTINUE
C
C     UPON EXITING DO LOOP 30, TPLUS(N) & TMINUS(N) HAVE BEEN COM-
C   PUTED.  STPIN IS THE SIN OF THETAP(1,N), CTPIN IS ITS COSINE,
C   AND STMIN & CTMIN ARE THEIR COUNTERPARTS FOR THE REVERSED PRO-
C   FILE.  THEN VPLUS(N) & VMINUS(N) ARE COMPUTED USING EQUATIONS
C   4 AND 5, RESPECTIVELY.
C
    40    TPLUS(N) = TPLUSN
          TMINUS(N) = TMINUN
C
          VMINUS(N) = ALPHA(1)/(STPIN*COSP1 + CTPIN*SINP1)
          VPLUS(N) = ALPHA(1)/(STMIN*COSP1 - CTMIN*SINP1)
    50 CONTINUE
C
C    ****  PRINT THE RESULTS OF THE PROGRAM  ****
C
        PRINT 9300
  9300     FORMAT (1H0,//,16X,'*****  CALCULATED RESULTS   *****',//,
       &     5X,'THE HORIZONTAL PHASE VELOCITIES AND THE ',
       &            'INTERCEPT TIMES',/,
       &     5X,'FOR THE DIRECT (+) AND REVERSED (-) PROFILES,',///,
       &   4X,'INTERFACE NO.  PHASE VEL+   PHASE VEL-',8X,'T+',9X,'T-')
C
        DO 60 N=2,NLAYRS
        VPLUS(N)=VPLUS(N)*1000
        VMINUS(N)=VMINUS(N)*1000
           PRINT 9400,N,VPLUS(N),VMINUS(N),TPLUS(N),TMINUS(N)
        VPLUS(N)=VPLUS(N)/1000
        VMINUS(N)=VMINUS(N)/1000
  9400           FORMAT (1H0,7X,I2,3X,2F13.3,3X,2F11.1)
     60 CONTINUE
        GOTO 999
C
   900 PRINT 9900
  9900     FORMAT (1H1,9X,'CHECK YOUR INPUT VELOCITIES ',/,
```

```
     &     5X,'THEY ARE NOT MONOTONICALLY INCREASING,')
      GO TO 3000
C
999   CONTINUE
C ****PLOT REFRACTION PROFILE LINES(T/D PLOT) ********
C *****PLOT DIRECT PROFILE LINE *****
2605 PRINT 7240
7240 FORMAT(1H1,4X,'INPUT 1 IF YOU  WISH TO PLOT FORWARD',/,
     &4X,'PROFILE LINE ONLY',/,4X,'ENTER 2 TO PLOT FORWARD AND REVERSE
     &PROFILE')
      READ 1000,M
      Y(1)=0
      X(1)=0
      X(2)=TPLUS(2)/(1/ALPHA(1)-1/VPLUS(2))
     Y(2)=(1/ALPHA(1))*X(2)
     K=3
      DO 70 N=2,NLAYRS-1
        X(K)=(TPLUS(N+1)-TPLUS(N))/(1/VPLUS(N)-1/VPLUS(N+1))
        Y(K)=TPLUS(N)+(1/VPLUS(N))*X(K)
     INTEGER D
        K=K+1
  70    CONTINUE
      X(K)=SPRDLN
      Y(K)=TPLUS(NLAYRS)+(1/VPLUS(NLAYRS))*X(K)
      IF(M.EQ.1) GO TO 2900
C***PLOT REVERSE PROFILE LINE ****
      K=K+1
      X(K)=SPRDLN
      Y(K)=0
      K=K+1
       X(K)=TMINUS(2)/(1/ALPHA(1)-1/VMINUS(2))
       Y(K)=(1/ALPHA(1))*X(K)
      X(K)=SPRDLN-X(K)
      K=K+1
      DO 80 N=2,NLAYRS-1
       X(K)=(TMINUS(N+1)-TMINUS(N))/(1/VMINUS(N)-1/VMINUS(N+1))
       Y(K)=TMINUS(N)+(1/VMINUS(N))*X(K)
     X(K)=SPRDLN-X(K)
       K=K+1
 80   CONTINUE
       X(K)=SPRDLN
       Y(K)=TMINUS(NLAYRS)+(1/VMINUS(NLAYRS))*X(K)
       X(K)=0
2900  YMAX=Y(1)
      DO 89 KK=2,K
      YMAX=MAX(YMAX,Y(KK))
 89    CONTINUE
      PRINT 8500,YMAX
8500  FORMAT(1H1,4X,'LARGEST VALUE OF Y FOR SCALING IS:',2X,F6.1)
    CALL PLOT2(X,Y,K)
5000   STOP
       END
      SUBROUTINE CHMINUS(HPLUS,SPRDLN,N,P,DELTA,HMINUS)
      DIMENSION HPLUS(10),DELTA(10),HMINUS(10)
      INTEGER D
```

```
      SUMCOS=1.0
      DO 93 D=1,N-1
      SIGH=DELTA(D+1)-DELTA(D)
      SUMCOS=SUMCOS*COS(SIGH*P)
   93 CONTINUE
      SIGH=DELTA(N+1)-DELTA(N)
      HMINUS(N)=HPLUS(N)-SPRDLN*SIN(SIGH*P)*SUMCOS
      RETURN
      END
```

APPENDIX J: REFRINV EXAMPLE AND LISTING

The following procedure is used by REFRINV to determine: 1) the layer velocities, α_n, 2) the layer "thicknesses", $H_n^{\pm}$, and the interface dip angles, δ_n, for layers with plane dipping interfaces all having the same strike. The given or input data are: 1) the intercept time, $T_{on}^{\pm}$, and 2) the horizontal phase velocities, $V_n^{\pm}$, for direct and reversed refraction profiles. All arrival times are assumed to be measured on the surface and the + and - signs refer to the quantities associated with the direct and the reversed profiles, respectively.

The velocity in the top layer, α_1, is given because it is the horizontal phase velocity of the direct p wave (and has the same value for both the direct and the reversed profiles). The intercept times of the direct waves, $T_{01}^{\pm}$, for these profiles are both zero and the dip angle of the top surface (the n=1 "interface"), δ_1, is defined to the zero.

The computation, therefore, is started with the data from the second interface (i.e., the first refraction) corresponding to *n=2* and proceeds as follows:

Compute

$$\text{ANGMNP,M} = \theta_{12} + \psi_1 = \arcsin(\alpha / V_2^{\pm})$$
$$= \text{ANGNNP,M}$$

and obtain

$$\alpha_1/\alpha_2 = \sin\theta_{12} = \sin .5(\text{ANGNNP} + \text{ANGNNM})$$
$$\alpha_2 = \alpha_1/\sin\theta_{12}$$
$$\psi_1 = .5\ (\text{ANGNNP} - \text{ANGNNM})$$

$$\text{TEMP2} = \alpha_1/(2\cos\theta_{12})$$
$$H_1^{\pm} = T_{02}^{\pm}\text{TEMP2}$$

thus, we have computed α_2, ψ_1(or δ_2) and $H_1^{\pm}$.

Then, for n=3, we compute

$$\text{ANGMNP,M} = \theta_{13}^{\pm} \pm \psi_1 = \arcsin(\alpha_1/V_3^{\pm})$$

and we enter DO-loop 30, to compute

$$\text{THETAP,M} = \theta_{13}^{\pm} = \text{ANGMNP,M} \mp \psi_1$$

$$\text{ANGMNP,M} = \theta_{23} \pm \psi_2 = \arcsin(\alpha_2 \sin\theta_{13}^{\pm}/\alpha_1)$$

$$\text{TEMP1} = (\cos\theta_{13}^{+} + \cos\theta_{13}^{-})/\alpha_1$$

$$\text{TPLUSN, TMINSN} = T_{03}^{\pm} - H_1^{\pm}\text{TEMP1}.$$

We then exit DO-loop 30 and compute

$$\text{ANGNNP,M} = \text{ANGMNP,M}$$

$$\alpha_3/\alpha_2 = \sin\theta_{23} = \sin.5(\text{ANGNNP} + \text{ANGNNM})$$

$$\alpha_3 = \alpha_2/\sin\theta_{23}$$

$$\psi_2 = .5(\text{ANGNNP} - \text{ANGNNM})$$

$$\text{TEMP2} = \alpha_2/(2\cos\theta_{23})$$

$$H_2^{\pm} = (T_{03}^{\pm} - H_1^{\pm}\text{TEMP1})\ \text{TEMP2}$$

Thus, we have computed α_3, ψ_2(or $\delta_3=\delta_2+\psi_2$) and $H_2^{\pm}$ as well as the previous values of α_2, ψ_1, and $H_1^{\pm}$ by using the data from the first two refractions, that is, the refractions along interfaces n=2 and n=3. (See Figure 1).

For n=4, we use the above results and the data from the refractions along the n=4 interface ($V_4^{\pm}$ and $T_{04}^{\pm}$) as follows: we compute

$$\text{ANGMNP,M} = \theta_{14}^{\pm} \pm \psi_1 = \arcsin(\alpha_1/V_4^{\pm}$$

and then enter DO-loop 30 to compute

$$\text{THETAP,M} = \theta_{14}^{\pm} = \text{ANGMNP,M} \mp \psi_1$$

$$\text{ANGMNP,M} = \theta_{24}^{\pm} \pm \psi_2 = \arcsin(\alpha_2 \sin\theta_{14}^{\pm}/\alpha_1)$$

$$\text{TEMP 1} = (\cos\theta_{14}^{+} + \cos\theta_{14}^{-})/\alpha_1$$

$$\text{TPLUSN,TMINSN} = T_{03}^{\pm} - H_1^{\pm}\ \text{TEMP 1}$$

$$\text{THETAP,M} = \theta_{24}^{\pm} = \text{ANGMNP,M} \mp \psi_2$$

$$\text{ANGMNP,M} = \theta_{34} \pm \psi_3 = \arcsin(\alpha_3 \sin\theta_{24}^{\pm}/\alpha_2)$$

$$\text{TEMP 1} = (\cos\theta_{24}^{+} + \cos\theta_{24}^{-})/\alpha_2$$

$$\text{TPLUSN,TMINSN} = \text{TPLVS, TMINSN} - H_2^{\pm}\ \text{TEMP1}.$$

We then exit DO-loop 30 and compute

$$\text{ANGNNP,M} = \text{ANGMNP,M}$$

$$\alpha_4/\alpha_3 = \sin\theta_{34} = \sin .5\ (\text{ANGNNP} + \text{ANGNNM})$$

$$\alpha_4 = \alpha_3/\sin\theta_{34}$$

$$\psi_3 = .5(\text{ANGNNP-ANGNNM})$$

$$\text{TEMP2} = \alpha_3/(2\cos\theta_{34})$$

$$H_3^{\pm} = (\text{TPLUSN,TMINSN})\text{TEMP2}.$$

Thus, we have computed α_4, ψ_3 (or $\delta_4 = \delta_3 + \psi_3$) and $H_3^{\pm}$. We now have all the parameters for a four-layer model (three layers over a half space).

The data are tabulated with all the data for a particular layer on one line in the following order: 1) the layer number, 2) the layer velocity, 3) the dip of the top interface, 4) the layer "thickness" for the direct profile and 5) the layer "thickness" for the reversed profile.

```
C    REFRAC 2 IS AN INVERSE PROGRAM.  IT DETERMINES MODEL PARAMETERS
C  FROM MEASURED VALUES.
C
C    PROGRAM REFRAC 2 HAS FOR ITS INPUT:
C         (FROM DIRECT AND REVERSED PROFILES)
C      1) HORIZONTAL PHASE VELOCITIES AND
C      2) INTERCEPT TIMES FOR EACH REFRACTION AND
C      3) THE VELOCITY IN THE FIRST LAYER.
C
C     REFRAC 2 COMPUTES AS OUTPUT:
C       1) THE VELOCITY IN  EACH LAYER,
C       2) THE DIP (IN DEGREES) OF EACH LAYER INTERFACE AND
C       3) THE LAYER THICKNESSES FOR THE DIRECT AND REVERSED
C          PROFILES.
C
C     PROGRAM REFRAC 2 IS THE INVERSE OF THE MODELLING PROGRAM
C   REFRAC 1.
C
C
C            *** LIST OF VARIABLES AND THEIR MEANINGS ***
C
C   ALPHA(N) = THE VELOCITY (OR WAVE SPEED) IN THE NTH LAYER
C
C   ANGMNM = (ANGLE(M,N)MINUS) = THETAM(M,N) - PSI(M) =
C          = ARSIN(SIN(THETAM)/SPEEDR(M))    (SEE EQN'S 1B, 2B & 3B)
C
C   ANGMNP = (ANGLE(M,N)PLUS) = THETAP(M,N) + PSI(M) =
C          = ARSIN(SIN(THETAP)/SPEEDR(M))    (SEE EQN'S 1A, 2A & 3A)
C
C   ANGNNM = (ANGLE(N-1,N)MINUS) = THETA(N-1,N) + PSI(N-1) =
C          = ARSIN(SIN(THETAM)/SPEEDR(N-1))    (SEE EQUATION 3B)
C
C   ANGNNP = (ANGLE(N-1,N)PLUS) = THETA(N-1,N) + PSI(N-1) =
C          = ARSIN(SIN(THETAP)/SPEEDR(N-1))    (SEE EQUATION 3A)
C
C   C = CONVERSION FACTOR, RADIANS TO DEGREES = 57.29578
C
C   DELTN = THE DIP ANGLE OF THE NTH INTERFACE
C
C   HMINUS(N) = THE LAYER "THICKNESS" FOR THE NTH LAYER, REVERSED
C        PROFILE.  (SEE FIGURE 1)
C
C   HPLUS(N) = THE LAYER "THICKNESS" FOR THE NTH LAYER, DIRECT
C        PROFILE.  (SEE FIGURE 1)
C
C   NLAYRS = (NUMBER OF LAYERS) = THE NUMBER OF LAYERS FOR WHICH
C        VELOCITIES WILL BE CALCULATED
C
C   NM1 = (N MINUS 1) = N-1
C
C   NX2LST = (NEXT TO LAST) = THE NUMBER OF THE NEXT-TO-LAST LAYER
C
C   PSI(N) = THE ANGLE BETWEEN THE SURFACES OF THE NTH LAYER
C
C   SPEEDR(N) = (SPEED RATIO) = SPEDRN = THE VELOCITY IN THE
```

```
C       (N-1)ST LAYER DIVIDED BY THE VELOCITY IN THE NTH LAYER
C
C  THETAM = (THETA MINUS) = THETAM(I,N) = THE ANGLE BETWEEN THE
C       ITH-INTERFACE NORMAL AND THE RAY OF THE WAVE THAT REFRACTS
C       ALONG THE NTH INTERFACE (N>1).  THIS IS FOR A DOWNWARD-
C       TRAVELLING WAVE.   .(SEE FIGURE 1)
C
C  THETAP = (THETA PLUS) = THETAP(I,N) = SAME AS THETAM EXCEPT
C       THIS IS FOR AN UPWARD-TRAVELLING WAVE.   (SEE FIGURE 1)
C
C  TMINUS(N) = THE INTERCEPT TIME FOR THE NTH REFRACTION (FOR
C       THE REVERSED PROFILE)
C
C  TMINSN = THE RUNNING (DECREMENTING) SUM OF THE INTERCEPT TIMES
C       USED TO COMPUTE HMINUS  (SEE EQUATION 9)  FOR THE REVERSED
C      PROFILE.
C
C  TPLUS(N) = SAME AS TMINUS(N), EXCEPT FOR THE DIRECT PROFILE
C
C  TPLUSN = SAME AS TMINSN, EXCEPT FOR THE DIRECT PROFILE
C
C  VMINUS(N) = (VELOCITY MINUS) = HORIZONTAL PHASE VELOCITY FOR
C       THE REVERSED PROFILE DUE TO A REFRACTION ON THE NTH
C       INTERFACE.
C
C  VPLUS(N) = (VELOCITY PLUS) = HORIZONTAL PHASE VELOCITY FOR
C       THE DIRECT PROFILE DUE TO A REFRACTION ON THE NTH
C       INTERFACE.
C
C  V1 = THE VELOCITY IN THE FIRST LAYER
C
C
C                 *****  EQUATIONS USED  *****
C
C  THETAP(1,N) + PSI(1) = ARSIN(ALPHA(1)/VMINUS(N))
C                       = ANGMNP    (M=1)                     (1A)
C
C  THETAM(1,N) - PSI(1) = ARSIN(ALPHA(1)/VPLUS(N))
C                       = ANGMNM    (M=1)                     (1B)
C
C  THETAP(M,N) + PSI(M) = ARSIN(SIN(THETAP(M-1,N))/SPEEDR(M))
C                       = ANGMNP                              (2A)
C
C  THETAM(M,N) - PSI(M) = ARSIN(SIN(THETAM(M-1,N))/SPEEDR(M))
C                        = ANGMNM                             (2B)
C
C   THETA(N-1,N) + PSI(N-1) = ARSIN(SIN(THETAP(N-2,N))/SPEEDR(N-1))
C                        = ANGNNP    (M=N-1)                  (3A)
C
C   THETA(N-1,N) - PSI(N-1) = ARSIN(SIN(THETAM(N-2,N))/SPEEDR(N-1))
C                        = ANGNNM    (M=N-1)                  (3B)
C
C   ALPHA(N-1)/ALPHA(N) = SIN(THETA(N-1,N)) = SIN(.5*(ANGNNP+ANGNNM))
C                       = SPEEDR(N) = SPEDRN                  (4)
C
```

```
C   PSI(N-1) = 0.5*(ANGNNP - ANGNNM)                                 (5)
C
C   TEMP1 = (COS(THETAP) + COS(THETAM))/ALPHA(N-1)                   (6)
C
C   TEMP2 = 0.5*ALPHA(N-1)/SQRT(1. - SPEDRN**2)                      (7)
C
C   HPLUS(N-1) = TEMP2*(TPLUS(N) - SUM FROM I=1 TO N-2 OF
C                    HPLUS(I)*TEMP1)                                  (8)
C
C   HMINUS(N-1) = TEMP2*(TMINUS(N) - SUM FROM I=1 TO N-2 OF
C                    HMINUS(I)*TEMP1)                                 (9)
C
C
C                  *************************************
C                  *****  START PROGRAM REFRAC 2 *****
C                  *************************************
C
C     ***  INPUT
        REAL VPLUS(50),VMINUS(50),TPLUS(50),TMINUS(50)
C
C     ***  OUTPUT
        REAL ALPHA(50),HPLUS(50),HMINUS(50),DELTN
C
C     ***  VARIABLES
        REAL SPEEDR(50),PSI(50)
C
C                       ****** READ MODULE ******
C
        READ 1000,NLAYRS,V1
 1000 FORMAT(V)
C  DECIMAL POINT IN COLUMN 11
        ALPHA(1)=V1
        NX2LST=NLAYRS-1
C
        DO 10 N=2,NLAYRS
      READ 1000,VPLUS(N),VMINUS(N),TPLUS(N),TMINUS(N)
C  DECIMAL POINTS IN COLUMNS 3,11,21 AND 29
   10     CONTINUE
C
C                       ****** PRINT MODULE ******
C
        PRINT 9000,NX2LST,V1
 9000     FORMAT (1H1,4X,'VELOCITIES ARE IN METERS/MILLISEC, ',
     &           'TIMES ARE IN MILLISEC',/,
     &    5X,'AND LAYER THICKNESSES IN METERS',//,
     &    5X,'NO. OF REFRACTIONS = ',I2,': FIRST-LAYER ',
     &           'VELOCITY IS:',F7.3,///,
     &    5X,'INPUT DATA:  PHASE VELOCITIES AND ',
     &           'INTERCEPTS OF REFRACTIONS',/,
     &    5X,'MEASURED ON DIRECT (+) AND REVERSED (-) PROFILES',//,
     &    4X,'INTERFACE NO.  PHASE VEL+   PHASE VEL-     T+',
     &           9X,'T-')
C
        DO 15 N=2,NLAYRS
          PRINT 9100,N,VPLUS(N),VMINUS(N),TPLUS(N),TMINUS(N)
```

```
9100        FORMAT (1H0,I9,4X,2F13,3,2F11,1)
   15    CONTINUE
C
C
C                    ****** COMPUTATION MODULE *****
C
C  ALL CALCULATIONS ARE PERFORMED IN DO-LOOP 40
C
      DO 40 N=2,NLAYRS
C
C  USE EQUATIONS 1A & 1B TO FIND ANGMNP & ANGMNM   (M=1)
         ANGMNP = ARSIN(V1/VMINUS(N))
         ANGMNM = ARSIN(V1/VPLUS(N))
C
         TPLUSN = TPLUS(N)
         TMINSN = TMINUS(N)
            NM1 = N-1
C  IF THE FIRST LAYER'S PARAMETERS ARE BEING COMPUTED,
C          SKIP DO-LOOP 30 (GOTO 35)
       IF (N .EQ. 2) GOTO 35
C
C  DO-LOOP 30 COMPUTES THE SUMS IN EQUATIONS 8, AND 9.
C
            DO 30 M=2,NM1
C
C  USE EQUATIONS 2A & 2B TO FIND THETAP & THETAM
               THETAP = ANGMNP - PSI(M-1)
               THETAM = ANGMNP + PSI(M-1)
C  USE EQUATIONS 2A & 2B TO FIND NEW ANGMNP & ANGMNM
               ANGMNP = ARSIN(SIN(THETAP)/SPEEDR(M))
               ANGMNM = ARSIN(SIN(THETAM)/SPEEDR(M))
C
               TEMP1 = (COS(THETAP) + COS(THETAM))/ALPHA(M-1)
               TPLUSN = TPLUSN - HPLUS(M-1)*TEMP1
               TMINSN = TMINSN - HMINUS(M-1)*TEMP1
  30           CONTINUE
C
C  UPON EXITING DO-LOOP 30, ANGMNP & ANGMNM ARE (SEE EQNS 3A & 3B)
C      THETA(N-1,N) +/- PSI(N-1), RESPECTIVELY
C      (THAT IS, ANGNNP & ANGNNM, RESPECTIVELY)
C
  35     ANGNNP = ANGMNP
         ANGNNM = ANGMNM
C
C  USE EQN 4, FIND SPEEDR(N) = ALPHA(N-1)/ALPHA(N), THEN ALPHA(N)
         SPEDRN = SIN(0,5*(ANGNNP + ANGNNM))
         SPEEDR(N) = SPEDRN
         ALPHA(N) = ALPHA(NM1)/SPEDRN
C
C  USE EQUATION 5 TO FIND PSI(N-1)
         PSI(NM1) = 0,5*(ANGNNP - ANGNNM)
C
C  USE EQUATIONS 8 & 9 TO FIND HPLUS(N-1) & HMINUS(N-1)
         TEMP2 = ALPHA(NM1)/(2,*SQRT(1, - SPEDRN*SPEDRN))
         HPLUS(NM1)  = TPLUSN*TEMP2
```

```
          HMINUS(NM1) = TMINSN*TEMP2
   40  CONTINUE
C
C                  ****** OUTPUT PRINT MODULE *****
C
       PRINT 9500
 9500     FORMAT (1H0,//,16X,'*****  CALCULATED RESULTS  *****',//,
     &        5X,'THE WAVE VELOCITIES, INTERFACE DIPS AND ',
     &          'LAYER THICKNESSES',///,
     &        6X,'LAYER NO.    VELOCITY   DIP (DEG)   H+',8X,'H-')
C
        DELTN = 0.0
        C = 57.29578
C
       DO 50 N=1,NX2LST
          PRINT 9600,N,ALPHA(N),DELTN,HPLUS(N),HMINUS(N)
 9600        FORMAT (I10,9X,F6.3,3F10.1)
C  CALCULATE DELTN; CONVERT ANGLES FROM RADIANS TO DEGREES
          DELTN = C*PSI(N) + DELTN
   50  CONTINUE
C
        PRINT 9700,NLAYRS,ALPHA(NLAYRS),DELTN
 9700      FORMAT (I10,9X,F6.3,F10.1,////)
       STOP
       END
```

APPENDIX K: CROSSHOLE LISTING


```
10        CALL FPARAM(1,80)
20C          THIS PROGRAM WAS WRITTEN BY GEORGE R. SKOGLAND AND CHECKED
30C*************** CROSSHOLE SEISMIC INTERPRETATION *********************
40C       AND MODIFIED BY DWAIN K. BUTLER (1977) TO HELP
50C       DEVELOP A PLAUSIBLE TRUE VELOCITY INTERPRETATION FROM THE APPARENT
60C       VELOCITY PROFILE MEASURED IN THE FIELD BY CROSSHOLE SEISMIC
70C       TECHNIQUES.  TRAVEL PATHS ARE ASSUMED TO BE GOVERNED BY SNELL'S
80C       LAW OF REFRACTION.
90C          FROM THE INTERPRETED TRUE VELOCITY PROFILE, A COMPUTED
100C       APPARENT VELOCITY PROFILE IS DERIVED FOR COMPARISON WITH THE
110C       FIELD MEASURED DATA.  IN ADDITION, AN OPTION IS AVAILABLE TO
120C       INPUT ANY TRUE VELOCITY PROFILE FROM WHICH AN APPARENT VELOCITY
130C       PROFILE CAN BE CONSTRUCTED AS A FUNCTION OF A SPECIFIED HOLE
140C       SPACING AND DEPTH INTERVAL CONFIGURATION.
150
160
170C       USER HINTS (JULY 1977)
180
190C        1. THIS PROGRAM CAN BE USED FOR SHEAR WAVE AS WELL AS COMPRESSION
200C       WAVE VELOCITIES.
210
220C        2. THE FUNDAMENTAL INTERPRETATION CAPABILITY OF THIS PROGRAM IS
230C       BASED UPON THE MEASUREMENT OF ONE TRUE VELOCITY IN EACH VELOCITY
240C       LAYER.  THE WIDEST POSSIBLE HOLE SPACING THAT WILL GIVE ONE
250C       MEASURED TRUE VELOCITY IN EACH VELOCITY LAYER IS PREFERRABLE TO
260C       A CLOSER SPACING, BECAUSE ONLY APPARENT VELOCITIES DEFINITIVELY
270C       ESTABLISH VELOCITY LAYER INTERFACES.  IN GENERAL, THE IDEAL DATA
280C       BASE FOR EACH VELOCITY LAYER WOULD HAVE TWO APPARENT VELOCITIES
290C       RELATIVE TO THE SAME INTERFACE AND ONE TRUE VELOCITY.
300
310C        3. THE INTERPRETATION OF A PROFILE BEGINS AT THE HIGHEST GEOPHONE
320C       AND PROCEEDS DOWNWARD.  UNLESS OTHERWISE SPECIFIED, THE FIRST
330C       VELOCITY IS ASSUMED TO BE A TRUE VELOCITY WITH SUCCESSIVE
340C       VELOCITIES THEN SCRUTINIZED FOR INTERPRETATION UNTIL THE NEXT
350C       TRUE VELOCITY IS ENCOUNTERED.  IN CONCEPT, THE PROGRAM MOVES DOWN
360C       THE PROFILE FROM TRUE VELOCITY TO TRUE VELOCITY WITH ANY NUMBER OF
370C       APPARENT VELOCITIES (OR NONE AT ALL) IN BETWEEN ADJACENT TRUE
380C       VELOCITIES.
390
400C        4. IF A FIELD MEASURED PROFILE DOES NOT CONTAIN A MEASURED TRUE
410C       VELOCITY IN EACH VELOCITY LAYER, THE OPTION TO INPUT A TRUE
420C       VELOCITY PROFILE CAN GENERATE A COMPUTED APPARENT VELOCITY PROFILE
430C       THAT WILL COINCIDE WITH THE FIELD MEASURED PROFILE IF THE
440C       HYPOTHESIZED TRUE VELOCITY PROFILE IS A VALID POSSIBILITY.
450
460C        5. AN INPUT OPTION IS AVAILABLE TO SPECIFY THE DEEPEST TRUE
470C       VELOCITY.  SINCE MOST BOREHOLES END AT A HARDER MATERIAL THAN
480C       ENCOUNTERED ELSEWHERE IN THE PROFILE, THE MINIMUM TIME PATH AT
490C       THE BOTTOM OF THE BOREHOLE PROBABLY GOES DEEPER THAN THE BOREHOLE
500C       DEPTH.  THE DEPTH TO THE LAST VELOCITY MAY ALSO BE SPECIFIED IF
510C       A DEPTH GREATER THAN THE DEEPEST GEOPHONE IS DESIRED.
520
530C        6. TRAVEL PATHS ARE ASSUMED TO BEGIN AND END IN THE SAME VELOCITY
540C       LAYER, ALTHOUGH NOT NECESSARILY AT THE SAME DEPTH.
550
```

```
C      7. HOLE COORDINATES ARE NORTH POSITIVE, EAST POSITIVE, AND DEPTH.


C     FUTURE IMPROVEMENTS

C      1. PROVIDE FOR A TRAVEL PATH TO BEGIN IN ONE LAYER AND END IN
C     THE ADJACENT LAYER.  THIS CAPABILITY WILL ALLOW FOR MORE
C     SOPHISTICATED SOURCE-GEOPHONE AND MULTIPLE GEOPHONE CONFIGURATIONS

C      2. PROVIDE FOR A SPECIFIED INTERFACE SLOPE.

C      3. PROVIDE A MODEL TO GENERATE A MEISSNER WAVE FRONT DIAGRAM
C     FOR COMPARISON WITH A MEISSNER WAVE FRONT SURVEY TO BE
C     CONDUCTED IN CONJUNCTION WITH THE CROSSHOLE SURVEY.

C      4. INCORPORATE UPHOLE TIMES TO AID IN THE INTERPRETATION AND TO
C     PROVIDE VERTICAL WAVE VELOCITIES (IN A SIMILAR MANNER TO THE
C     U.S. BUREAU OF MINES PROGRAM FOR REFRACTION SEISMIC PROFILING)
C     FOR CROSSHOLE SURVEYS.

C**** PROGRAM INPUT ***********************************************************

C     FIRST CARD - FORMAT (12A6)
C        1-72  DATA IDENTIFICATION
C

C     SECOND LIST - FORMAT (4I5,4F10.0,2I5)
C        1-5    INPUT OPTION CODE
C                 1 FOR ARRIVAL TIMES
C                 2 FOR APPARENT VELOCITIES
C                 3 FOR TRUE VELOCITY PROFILE AND ARRIVAL TIMES
C                 4 FOR TRUE VELOCITY PROFILE AND APPARENT VELOCITIES
C                 5 FOR TRUE VELOCITY PROFILE
C        6-10  STORAGE KEY FOR USE WITH OUTPUT OPTIONS
C       11-15  OUTPUT OPTION CODE
C                 1 FOR TABDUM-APPARENT VELOCITY AS A FUNCTION OF HOLE S
C                 2 FOR SUMARY
C                 3 FOR SUMTWO
C                 7 FOR CARRYING OVER THE PREVIOUS TRUE VELOCITY PROFILE
C       16-17  TYPE OF SUMMARY TABLE DESIRED (FOR USE WITH IOP2=2)
C                 1 FOR PARTIAL SUMMARY THREE HOLE SET
C                 2 FOR FULL SUMMARY THREE HOLE SET
C       18-20  NUMBER OF SHOT RECORDS PER HOLE SET
C       31-40  HOLE PAIR AZIMUTH
C        21-30  HORIZONTAL DISTANCE BETWEEN BOREHOLES
C        41-50  FIRST LAYER TRUE VELOCITY (IF NOT DEFINED BY THE DATA)
C        51-60  DEEPEST LAYER TRUE VELOCITY (IF NOT DEFINED BY THE DATA)
C        61-65  DEPTH TO THE DEEPEST LAYER (IF KNOWN)
C        66-70  NUMBER OF TRUE VELOCITY LAYERS FOR INPUT OPTIONS 3,4,5
C        71-75  GEOPHONE SPACING (FOR USE WITH INPUT OPTION 5 ONLY)
C        76-80  OUTPUT PUNCH OPTION (FOR USE WITH OPTION 5)

C      THIRD LIST - FORMAT (8F10.0)
C         1-10  SHOTPOINT DEPTH (Z-COORDINATE)
C        11-20  SHOTPOINT LOCAL X-DEVIATION (NORTH DIRECTION POSITIVE)
```

```
C        21-30  SHOTPOINT LOCAL Y-DEVIATION (EAST DIRECTION POSITIVE)
C        31-40  GEOPHONE DEPTH (Z-COORDINATE)
C        41-50  GEOPHONE LOCAL X-DEVIATION
C        51-60  GEOPHONE LOCAL Y-DEVIATION
C        61-70  ARRIVAL TIME, SECONDS (FOR USE WITH INPUT OPTION 1 AND 3)
C        71-80  APPARENT VELOCITY (FOR USE WITH INPUT OPTION 2 AND 3)
       COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
     &              SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
     &             ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
       COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
     &,VC(20,20)
       COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
        CHARACTER*24 DIN(2)
       CHARACTER*60 TITLE
       DATA DIN(2)/1H;/
         ISTAT=0
         GO TO 2
1        CALL DETACH(1,ISTAT,)
2        PRINT 10
10      FORMAT("ENTER THE NAME OF THE DATA FILE YOU WANT TO PROCESS")
        READ 820,DIN(1)
        IF(DIN(1).EQ.8H        )GO TO 999
        CALL ATTACH(1,DIN,3,0,ISTAT,)
820    FORMAT(V)

       DATA AFAC / 0.02 /, CFAC / 0.05 /

      PRINT 895
        READ(1,800) TITLE
      READ(1,810)LIN,IOP1,N,IOP2,ISUM,M,DIST,AZIM,VFIRST,VLAST,DLLAST,IMAX,
      & DELGS,IPUN
       IF(N.EQ.0) N=1
       IF(IOP1.EQ.0) GO TO 250

       DO 200 I=1,20
       DL(I,N)=0.0
       VL(I,N)=0.0
       SVL(I,N)=0.0
  200 K(I,N)=0.0

  250 IF(M.GT.JMAX) JMAX=M

       IF(IOP1.EQ.0) GO TO 410

  400 CALLRINPUT (IOP1,N,IOP2,M,DIST,AZIM,IMAX)

  410 IF(IOP2.EQ.0) GO TO 500
       IF(IOP2.EQ.1) CALL TABDUM (M,IMAX)
       IF(IOP2.EQ.2) CALL SUMARY (JMAX,ISUM)
       IF(IOP2.EQ.3) CALL SUMTWC (M,N)
       IF(IOP2.EQ.7) CALL CARRYC (M,N,LNIMAX)
       JMAX=0
       IF(IOP1.EQ.0) GO TO 1
       GO TO 600
```

```
 500 IF(IOP1.EQ.1.OR.IOP1.EQ.2) CALL CONTRO (I,J,M,N,IMAX,AFAC)

 600 CALL OPRIN1 (I,J,M,N,IMAX,SNDF,SSND,CFAC,IOP1)

     CALL STATS (M,SNDF,SSND)

     IF(IPUN.EQ.1) CALL UPUNCH (M,N,IMAX,DIST,AZIM)

     GO TO 1
 800 FORMAT(A64)
810  FORMAT(V)
 895 FORMAT (1H1)
 999 STOP
     END
     SUBROUTINERINPUT (IOP1,N,IOP2,M,DIST,AZIM,IMAX)

     COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
    &              SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
    &              ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
     COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
    &,VC(20,20)
     COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
     CHARACTER*60 TITLE

     PRINT 51, TITLE
  51 FORMAT(T2,"CROSSHOLE DATA *",A60,//)

     PRINT 800, DIST
 800 FORMAT ( 5X,36HHORIZONTAL DISTANCE BETWEEN HOLES IS,F6.1,//)

     IF(IOP1.NE.5) GO TO 600
     GZ(1)=DELGS
     SZ(1)=DELGS
     DO 500 J=2,M
     SZ(J)=SZ(J-1)+DELGS
 500 GZ(J)=GZ(J-1)+DELGS

 600 PRINT 810
 810 FORMAT(6X,5HDEPTH,4X,6HDIRECT,1X,7HARRIVAL,3X,8HAPPARENT,
    &5X,9HSHOT HOLE,5X,8HGEO HOLE,/,2X,4HSHOT,4X,3HGEO,2X,
    &8HDISTANCE,1X,4HTIME,3X,4HVELO,6X,5HX-DEV,3X,5HY-DEV,
    &3X,5HX-DEV,3X,5HY-DEV,//)

     ANGLE=0.01745*AZIM
     XFAC=DIST*COS(ANGLE)
     YFAC=DIST*SIN(ANGLE)

     DO 100 J=1,M

     SX(J)=0.0
     SY(J)=0.0
     GX(J)=0.0
 100 GY(J)=0.0

     IF(IOP1.EQ.5) GO TO 300
```

```
        DO 250 J=1,M
         IF(IOP1.EQ.1.OR.IOP1.EQ.3) READ (1,820)LIN,SZ(J),SX(J),SY(J),GZ(J),
       &     GX(J),GY(J)
         IF(IOP1.EQ.2.OR.IOP1.EQ.4) READ (1,830)LIN,SZ(J),SX(J),SY(J),GZ(J),
       &     GX(J),GY(J)
 250      CONTINUE
       DO 6 J=1,M
       IF(IOP1.EQ.1.OR.IOP1.EQ.3)READ(1,820)LIN,TR(J,N)
       IF(IOP1.EQ.2.OR.IOP1.EQ.4) READ(1,820)LIN,VA(J,N)
 6     CONTINUE
        IF(IOP1.EQ.2.OR.IOP1.EQ.4) GO TO 300
        DO 5 J=1,M
 5      TR(J,N)=TR(J,N)/1000.
 300      DO 200 J=1,M
        DFGS(J,N)=GZ(J)-SZ(J)
        SFGS(J,N)=(GX(J)+XFAC*SX(J))*(GX(J)+XFAC*SX(J))
        SFGS(J,N)=SFGS(J,N)+(GY(J)+YFAC*SY(J))*(GY(J)+YFAC*SY(J))
        SFGS(J,N)=SQRT(SFGS(J,N))
        SS(J,N)=0.0
        SG(J,N)=SS(J,N)+SFGS(J,N)
        DS(J,N)=SZ(J)
        DG(J,N)=GZ(J)
        HYPOSQ=DFGS(J,N)*DFGS(J,N)+SFGS(J,N)*SFGS(J,N)
        DP(J,N)=SQRT(HYPOSQ)
        IF(IOP1.EQ.1.OR.IOP1.EQ.3) VA(J,N)=DP(J,N)/TR(J,N)
        IF(IOP1.EQ.2.OR.IOP1.EQ.4) TR(J,N)=DP(J,N)/VA(J,N)
        IF(IOP1.EQ.5) VA(J,N)=0.0
        IF(IOP1.EQ.5) TR(J,N)=0.0
  200 PRINT 840, DS(J,N),DG(J,N),DP(J,N),TR(J,N),VA(J,N),SX(J),SY(J),
       &             GX(J),GY(J)

        IF(IOP1.EQ.1.OR.IOP1.EQ.2) GO TO 900
        READ (1,850) LIN,(DL(I,N),I=1,IMAX-1)
        READ (1,850)LIN,(VL(I,N),I=1,IMAX)
  860 FORMAT (//,32HSPECIFIED TRUE VELOCITY PROFILE      )
        PRINT 860
        DO 400 I=1,IMAX-1
  400 PRINT 865, VL(I,N),DL(I,N)
        PRINT 865, VL(IMAX,N)
  865 FORMAT (20X,F9.1,/,30X,F9.1)
        RETURN

  900 CONTINUE
        IF(VFIRST.GT.0.0) PRINT 872, VFIRST
        IF(VLAST.GT.0.0) PRINT 874, VLAST
        IF(DLLAST.GT.0.0) PRINT 876, DLLAST
        RETURN
  872 FORMAT (/,10X,50HTHE FIRST LAYER TRUE VELOCITY WAS SPECIFIED TO BE
       &    ,F8.0)
  874 FORMAT (/,10X,52HTHE DEEPEST LAYER TRUE VELOCITY WAS SPECIFIED TO
       &BE     ,F8.0)
  876 FORMAT (  10X,51HTHE DEPTH TO THE DEEPEST LAYER WAS SPECIFIED TO B
       &E       ,F7.1)
 820     FORMAT(V)
 830      FORMAT(V)
```

```
 840 FORMAT (T1,F6.1,T8,F6.1,T15,F6.1,T22,F7.4,T30,F7.0,T38,
    &2F6.2,T55,2F8.2)
850     FORMAT(V)
     END
     SUBROUTINE CONTRO (I,J,M,N,IMAX,AFAC)
     COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
    &                 SFGS(50,20),DFGS(50,20),TH(50,20),VA(50,20),DP(50,20)
     COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
     COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
       CHARACTER*60 TITLE
     PRINT 110,TITLE
 110  FORMAT (///,T2,"CROSSHOLE DIAGNOSTIC -",A60,///)
     I=1
     J=1
     IF(VFIRST.LE.0.0) GO TO 300
     IF(VFIRST.GT.0.0) PRINT 810, VFIRST
 810 FORMAT ( 2X,59HCAUTION - THE FIRST LAYER TRUE VELOCITY WAS SPECIFI
    &ED TO BE     ,F7.0)
     IF(VA(1,N)/VA(2,N).GT.1.0-AFAC.AND.VA(1,N)/VA(2,N).LT.1.0+AFAC) GO
    &TO 100
     GO TO 700
 100 PRINT 820, VA(1,N),DG(1,N),VA(1,N),DG(1,N)
 820 FORMAT(12X,18HHOWEVER, SINCE THE,F7.0,3H AT,F6.1,21H IS APPARENTLY
    & A TRUE/12X,57HVELOCITY, THE INTERFACE BETWEEN THE SPECIFIED FIRST
    & LAYER/12X,17HTRUE VELOCITY AND,F7.0,22H MAY BE SHALLOWER THAN,F6.
    &1,8H.  CHECK/12X,45HSEISMIC REFRACTION DATA FOR THIS POSSIBILITY.)
 300 IF(J.EQ.M) GO TO 400
     IF(J.GT.M) RETURN
     AR=VA(J,N)/VA(J+1,N)
     IF(AR.GT.1.0-AFAC.AND.AR.LT.1.0+AFAC) GO TO 400
     IF(AR.LE.1.0-AFAC) GO TO 700
     IF(AR.GE.1.0+AFAC) GO TO 200
 400 VL(I,N)=VA(J,N)
     SVL(I,N)=SVL(I,N)+VL(I,N)
     K(I,N)=K(I,N)+1
     IMAX=I
     J=J+1
     GO TO 300
 200 CALL UPTIME (I,J,M,N,IMAX)
     GO TO 300
 700 CALL DOWNTM(I,J,M,N,IMAX)
     GO TO 300
     RETURN
     END
     SUBROUTINE UPTIME(I,J,M,N,IMAX)
     COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
```

```
     &             SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20)

C *** LOCATES INTERFACE FOR VELOCITIES DECREASING WITH DEPTH ***********

      IF(DG(J,N).EQ.DG(J+1,N).AND.DS(J,N).LE.DG(J+1,N)) GO TO 260
      JB=1
  205 JUU=J+JB

C ***********************************************************************
      PRINT 200, I,J,JB
  200 FORMAT (25X,'EXECUTION CHECK - LAYER',I3,' - DEPTH',I3,
     & ' - UP',I2)
C ***********************************************************************

      VL(I,N)=VA(J,N)
      VL(I+1,N)=VA(JUU,N)
      DL(I,N)=TR(J+1,N)
      ADJSQ=VL(I,N)*VL(I,N)-VL(I+1,N)*VL(I+1,N)
      ADJ=SQRT(ADJSQ)
      DL(I,N)=DL(I,N)-SFGS(J+1,N)/VL(I,N)
      DL(I,N)=DL(I,N)*VL(I,N)/ADJ
      DL(I,N)=0.5*DL(I,N)*VL(I+1,N)
      DL(I,N)=DL(I,N)-0.5*DFGS(J+1,N)
      DL(I,N)=DG(J+1,N)-DFGS(J+1,N)-DL(I,N)
      IF(DL(I,N).GT.DG(J,N).AND.DL(I,N).LE.DG(J+1,N)) GO TO 280
      IF(JUU.EQ.M) GO TO 280
      IF(VA(JUU,N).LT.VA(JUU+1,N)) GO TO 280
      JB=JB+1
      GO TO 205

  280 IF(DL(I,N).GT.DG(J,N).AND.VA(J,N).EQ.VL(I,N).AND.
     &VA(J+1,N).EQ.VL(I+1,N)) PRINT 527, DL(I,N),DG(J,N),DL(I,N)
      IF(DL(I,N).GT.DG(J+1,N).OR.DL(I,N).LE.DG(J,N)) DL(I,N)=DG(J,N)+1.0
      SVL(I,N)=SVL(I,N)+VL(I,N)
      K(I,N)=K(I,N)+1
      K(I+1,N)=K(I+1,N)+JB-1
      SVL(I+1,N)=SVL(I+1,N)+(JB-1)*VL(I+1,N)
      IMAX=I
      I=I+1
      J=J+JB
  527 FORMAT(T3,'CAUTION - THE INTERFACE CALCULATED TO BE AT',F6.1,
     &/T5,'COULD BE ANYWHERE BETWEEN',F6.1,' AND',F6.1)
      RETURN

  260 PRINT 550, VA(J,N),DG(J,N),VA(J+1,N),DG(J+1,N)
  550 FORMAT(T3,'CAUTION - THE',F7.0,' AT GEOPHONE DEPTH',F6.1,
     &'AND THE',F7.0,/'AT GEOPHONE DEPTH',F6.1,' SHOULD BE EQUAL.')
      VL(I,N)=VA(J,N)
      SVL(I,N)=SVL(I,N)+VL(I,N)
      K(I,N)=K(I,N)+1
      J=J+1
      RETURN

      END
```

```
      SUBROUTINE DOWNTM(I,J,M,N,IMAX)

      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
     &             SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20)
      COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
      CHARACTER*60 TITLE

C *** LOCATES INTERFACE FOR VELOCITIES INCREASING WITH DEPTH ***********

      JA=1
  705 JJJ=J+JA-1

C **********************************************************************
      PRINT 200, I,J,JA
  200 FORMAT(25X,'EXECUTION CHECK - LAYER',I3,' - DEPTH',I3,
     & ' - DOWN',I2)
C **********************************************************************

      VL(I,N)=VA(J,N)
      VL(I+1,N)=VA(J+JA,N)
      IF(I.EQ.1.AND.VFIRST.GT.0.0.AND.J.EQ.1) VL(1,N)= VFIRST
      IF(J+JA.GT.M.AND.VLAST.GT.0.0) VL(I+1,N)=VLAST

      DL(I,N)=TR(JJJ,N)
      ADJSQ=VL(I+1,N)*VL(I+1,N)-VL(I,N)*VL(I,N)
                IF(ADJSQ.LE.0.0) PRINT 501, DG(J,N)
      ADJ=SQRT(ADJSQ)
      DL(I,N)=DL(I,N)-SFGS(J,N)/VL(I+1,N)
                IF(DL(I,N).LT.0.0) PRINT 503, DG(J,N)
      DL(I,N)=DL(I,N)*VL(I+1,N)/ADJ
      DL(I,N)=0.5*DL(I,N)*VL(I,N)
      DL(I,N)=DL(I,N)-0.5*DFGS(J,N)
                IF(DL(I,N).LT.0.0) PRINT 505, DG(J,N)

      DL(I,N)=DL(I,N)+DFGS(JJJ,N)+DS(JJJ,N)
      IF(DG(J+JA,N).NE.DG(JJJ,N).AND.DL(I,N).LE.DG(J+JA,N).AND.
     &   DL(I,N).GT.DG(JJJ,N)) GO TO 720
      IF(DG(J+JA,N).EQ.DG(JJJ,N).AND.DL(I,N).LE.DS(J+JA,N).AND.
     &   DL(I,N).GT.DS(JJJ,N)) GO TO 720
      IF(J+JA.EQ.M.AND.VLAST.GT.0.0) GO TO 710
      IF(J+JA.GE.M) GO TO 780
      IF(VA(J+JA,N).GT.VA(J+JA+1,N)) GO TO 780
  710 JA=JA+1
      GO TO 705

  720 IF(JA.EQ.1.AND.J+2.LE.M) CALL DTCHEK (I,J,M,N,JA)

  780 IF(J+JA.GT.M) GO TO 790
      IF(DL(I,N).LT.DG(J+1,N).AND.VA(J,N).EQ.VL(I,N).AND.
     &VA(J+1,N).EQ.VL(I+1,N)) PRINT 527, DL(I,N),DL(I,N),DG(J+1,N)
      IF(J+JA.EQ.M.AND.DL(I,N).GT.DG(J+JA,N)) PRINT 525
     &,DG(JJJ,N),VA(JJJ,N),VA(J+JA,N),DG(J+JA,N)
      IF(J+JA.LT.M.AND.DL(I,N).GT.DG(J+JA,N).AND.
     & VA(J+JA,N).GT.VA(J+JA+1,N)) PRINT 530, DG(JJJ,N),VA(JJJ,N),
```

```
      &    VA(J+JA,N),DG(J+JA,N),VA(J+JA+1,N),DG(J+JA+1,N)

       IF(DL(I,N).GT.DG(J+JA,N).OR.DL(I,N).LT.DG(JJJ,N))
      &DL(I,N)=DG(J+JA,N)

       IF(DL(I,N).GT.DS(J+JA,N).OR.DL(I,N).LT.DS(JJJ,N).AND.
      &   DG(J+JA,N).EQ.DG(JJJ,N)) DL(I,N)=DS(J+JA,N)

   790 SVL(I,N)=SVL(I,N)+JA*VL(I,N)
       K(I,N)=K(I,N)+JA
       IMAX=I
       IF(J+JA.GT.M.AND.VLAST.GT.0.0.AND.DLLAST.GT.0.0) GO TO 800
       I=I+1
       J=J+JA
       RETURN

   800 PRINT 810,DLLAST,DL(I,N)
       IMAX=I+1
       SVL(IMAX,N)=VLAST
       K(IMAX,N)=1
       J=J+JA
       RETURN
   501 FORMAT (T13,'AT GEOPHONE DEPTH',F6.1,', NEGATIVE VELOCITY DIFFEREN
      &CE')
   503 FORMAT (T13,'AT GEOPHONE DEPTH',F6.1,', NEGATIVE TIME FACTOR')
   505 FORMAT (T13,'AT GEOPHONE DEPTH',F6.1,', NEGATIVE DEPTH FACTOR')
   525 FORMAT (T3,'CAUTION - AT GEOPHONE DEPTH',F6.1,', THE',F7.0,/,
      &' COULD BE APPARENT',T13,'AND OR THE',F7.0,
      &'SHOULD BE APPARENT')
   527 FORMAT(T3,'CAUTION - THE INTERFACE CALCULATED TO BE AT',F6.1,/' CO
      &ULD BE ANYWHERE BETWEEN',F6.1,' AND',F6.1)
   528 FORMAT (T3,'CAUTION - AT GEOPHONE DEPTH',F6.1,', IF THE',F7.0,' IS
      & A CORRECT VELOCITY ,',/,T13,'THEN THE ',F7.0,'AT GEOPHONE DEBTH',/
      &F6.1,' IS EITHER APPARENT OR INCORRECT.')
   530 FORMAT ( 2X,27HCAUTION - AT GEOPHONE DEPTH,F6.1, 4H THE,F7.0,
      & 18H COULD BE APPARENT,/,12X,10HAND/OR THE,F7.0, 3H AT,F6.1,
      &  7H OR THE,F7.0,/3H AT,F6.1,14H ARE INCORRECT)
   810 FORMAT(2X,'CAUTION - THE EDPTH TO THE HIGH VELOCITY LAYER BENEATH
      &THE ',/2X,' DEEPEST GEOPHONE WAS SPECIFIED TO BE ',F7.1,
      &' AND CALCULATED TO BE  ',F7.1)
       END
       SUBROUTINE DTCHEK (I,J,M,N,JA)

       COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
      &              SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
       COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
       COMMON/CONSTA/DELGS,VFIRST,VLAST,DLLAST,TITLE
        CHARACTER*60 TITLE

C *** CHECKS DOWNTH INTERPRETATION FOR POSSIBLE AMBIGUITIES AND
C               ASSUMES THE SIMPLIEST INTERPRETATION ********************

       IF(VA(J,N).GT.VA(J+2,N).OR.VA(J+1,N).GT.VA(J+2,N)) RETURN
       IF(DS(J+1,N).LT.DS(J,N).AND.DG(J+1,N).GT.DG(J,N)) RETURN

```

```
      L=0
      IF(J.EQ.1) L=1
      IF(L.EQ.1.AND.VFIRST.GT.0.0) PRINT 528,DG(1,N)
  528 FORMAT(1X,64HNOTE--THE FIRST LAYER TRUE VELOCITY WAS NOT SET
     &EQUAL TO VFIRST,/7X,52HCHECK SEISMIC REFRACTION DATA FOR POSSIBLE
     &INTFACE/7X,25HAT A SHALLOWER DEPTH THAN,F6.1)
      V2CH=VA(J+1,N)
      V3CH=VA(J+2,N)

      D2MN=TR(J+1,N)
      ADJSQ=V3CH*V3CH-V2CH*V2CH
      IF(ADJSQ.LE.0.0) GO TO 728
      ADJ=SQRT(ADJSQ)
      GO TO 729
  728 ADJ=0.0
  729 CONTINUE
      D2MN=D2MN-SFGS(J+1,N)/V3CH
      D2MN=D2MN*V3CH/ADJ
      D2MN=0.5*D2MN*V2CH
      D2MN=D2MN-0.5*DFGS(J+1,N)
      D2MN=D2MN+DFGS(J+1,N)+DS(J+1,N)

      IF(DG(J+1,N).NE.DG(J+2,N).AND.D2MN.GT.DG(J+1,N).AND.
     &   D2MN.LT.DG(J+2,N)) PRINT 529, DG(J+1,N),VA(J+1,N)
      IF(DG(J+1,N).EQ.DG(J+2,N).AND.D2MN.GT.DS(J+1,N).AND.
     &   D2MN.LT.DS(J+2,N)) PRINT 529, DS(J+1,N),VA(J+1,N)

  730 IF(J-1.EQ.0.OR.I-1.EQ.0) GO TO 770
      IF(VA(J-1,N).GT.VA(J,N)) GO TO 770
      IF(VL(I-1,N).NE.VA(J-1,N).OR.VL(I,N).NE.VA(J,N)) GO TO 770
      J=J-1
      I=I-1

  770 V1CH=VA(J,N)
      V2CH=VA(J+2,N)

      DPEX=TR(J+1,N)
      ADJSQ=V2CH*V2CH-V1CH*V1CH
      ADJ=SQRT(ADJSQ)
      DPEX=DPEX-SFGS(J+1,N)/V2CH
      DPEX=DPEX*V2CH/ADJ
      DPEX=0.5*DPEX*V1CH
      DPEX=DPEX-0.5*DFGS(J+1,N)
      DPEX=DPEX+DFGS(J+1,N)+DS(J+1,N)

      IF(DG(J+1,N).NE.DG(J+2,N).AND.DPEX.GT.DG(J+1,N).AND.
     &   DPEX.LT.DG(J+2,N)) GO TO 790
      IF(DG(J+1,N).EQ.DG(J+2,N).AND.DPEX.GT.DS(J+1,N).AND.
     &   DPEX.LT.DS(J+2,N)) GO TO 790
      RETURN

  790 VL(I,N)=VA(J,N)
      VL(I+1,N)=VA(J+2,N)
      DL(I,N)=DPEX
      JA=2
```

```
  529 FORMAT (T5,'CAUTION - AT GEOPHONE DEPTH',F6.1,', THE',F7.0,' COULD
     & BE A TRUE VELOCITY.')
      RETURN
      END
      SUBROUTINE OPRINT (I,J,M,N,IMAX,SNDF,SSND,CFAC,KTYPE)

      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
     &             SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
     &,VC(20,20)
      COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
        CHARACTER*60 TITLE

C *** OUTPUT PRINTOUT *****************************************************

       PRINT 114, TITLE
  114 FORMAT(///,T2,'CROSSHOLE INTERPRETATION -',A60)

      PRINT 805
  805 FORMAT(///,T4,'<INTERFACE DEPTH>',/T2,'GEO',T8,'SHOT',T16,'TRUE',T27,
     &'COMPUTED TRAVEL TIMES, SECONDS',T67,'APPARENT',
     &/T2,'DEPTH DEPTH   VELOCITY',T67,'APPARENT',
     &T24,'DIRECT',T32,'DOWN',T40,'DOWN',T48,'DOWN',T56,'UP',
     &T64,'COMPUTED',T72,'MEASURED',/T32,'1LAYER',T40,'2LAYER',
     &T48,'3LAYER',T56,'1LAYER',///)
      IF(KTYPE.EQ.1.OR.KTYPE.EQ.2) CALL TRUAV1 (IMAX,CFAC,N)


      I=1
      DO 890 J=1,M
  818 IF(DL(I,N).GT.DG(J,N)) GO TO 830
      IF(I.EQ.IMAX) GO TO 830
  820 FORMAT(T5,'<',T6,F6.1,T12,'>')
      PRINT 820, DL(I,N)

      IF(I+1.EQ.IMAX) GO TO 824
      IF(DG(J,N).GE.DL(I+1,N)) PRINT 822, VL(I+1,N)
  821 IF(DG(J,N) .LT.DL(I+1,N)) GO TO 824
  822  FORMAT(16X,F7.0)
      I=I+1
      GO TO 818
  824  I=I+1

  830 CALL TRTIM2(I,J,M,N,IMAX,NL,TT1,TT2,TT3,TT4)
      TT2U=999.
      IF(VL(I,N).GT.VL(I-1,N)) GO TO 827
      TT2U=SFGS(J,N)/VL(I-1,N)
      ADJSQ=VL(I-1,N)*VL(I-1,N)-VL(I,N)*VL(I,N)
      VV=SQRT(ADJSQ)
      TT2U=TT2U+(DFGS(J,N)+2.0*(DG(J,N)-DL(I-1,N)))*VV/(VL(I-1,N)*VL(I,N
     &))

  827 TMIN=AMIN1(TT1,TT2,TT3,TT4,TT2U)
      VLA=DP(J,N)/TMIN
      VC(J,N)=VLA
```

```

      CALL FOROUT (I,J,M,N,IMAX,NL,TT1,TT2,TT3,TT4,SNDF,SSND,VLA,IT2U,
     & TMIN)

  890 CONTINUE

          IF(I.GE.IMAX) GOTO900
      PRINT 820,DL(I,N)
      PRINT 840,VL(I+1,N)
  840     FORMAT(T17,F7.0)

  900 RETURN
      END
      SUBROUTINE TRUAVI(IMAX,CFAC,N)

      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20)
      COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
         CHARACTER*60 TITLE

C *** CONVERTS DETAILED LAYERING INTO REPRESENTATIVE LAYERING **********

  809 IC=0
      DO 806 I=1,IMAX
  806 VL(I,N)=SVL(I,N)/K(I,N)

      DO 808 I=1,IMAX-1
      IF(I.GE.IMAX-IC-1) GO TO 808
      RIR=VL(I,N)/VL(I+1,N)
      IF(K(I,N).GT.1.OR.K(I+1,N).GT.1) BFAC=0.05
      IF(K(I,N).EQ.1.AND.K(I+1,N).EQ.1) BFAC=0.10
      IF(RIR.LT.1.0-BFAC.OR.RIR.GT.1.0+BFAC) GO TO 808
      SVL(I,N)=SVL(I,N)+SVL(I+1,N)
      K(I,N)=K(I,N)+K(I+1,N)
      VL(I,N)=SVL(I,N)/K(I,N)
      IF(I+1.EQ.IMAX) GO TO 808
      DL(I,N)=DL(I+1,N)

      DO 807 II=I+1,IMAX-IC-1
      SVL(II,N)=SVL(II+1,N)
      K(II,N)=K(II+1,N)
      VL(II,N)=VL(II+1,N)
      IF(II.EQ.IMAX-IC-1) GO TO 807
      DL(II,N)=DL(II+1,N)
  807 CONTINUE
      IC=IC+1
  808 CONTINUE

      IMAX=IMAX-IC
      IF(IC.GE.1) GO TO 809

      IF(VLAST.EQ.0.0) RETURN
      IF(VLAST.GT.0.0.AND.VL(IMAX,N).EQ.VLAST) RETURN
      IF(DLLAST.EQ.0.0) RETURN
      DL(IMAX,N)=DLLAST
      IMAX=IMAX+1
```

```
      VL(IMAX,N)=VLAST

      RETURN
      END
      SUBROUTINE TRTIM2(I,J,M,N,IMAX,NL,TT1,TT2,TT3,TT4)

      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
     &            SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)

C *** COMPUTES TRAVEL TIMES FROM A TRUE VELOCITY PROFILE ***************

      TT(1)=999.
      TT(2)=999.
      TT(3)=999.
      TT(4)=999.
      NL=1
      TT(NL)=DP(J,N)/VL(I,N)
      IF(I.EQ.IMAX) GO TO 840
      IF(VL(I,N).GT.VL(I+1,N)) TT(2)=777.
      LF=0
      LC=0

  835 LC=LC+1
      NL=LC+1
      IF(TT(2).EQ.777.AND.NL.EQ.2) GO TO 835
      TT(NL)=SFGS(J,N)/VL(I+LC,N)
      ADJSQ=VL(I+LC,N)*VL(I+LC,N)-VL(I,N)*VL(I,N)
      ADJSQ=ABS(ADJSQ)
      ADJ=SQRT(ADJSQ)
      TT(NL)=TT(NL)+(DFGS(J,N)+2.0*(DL(I,N)-DG(J,N)))*ADJ/(VL(I+LC,N)*
     &VL(I,N))
      IF(I+1.EQ.IMAX) TT(3)=999.
      IF(I+1.EQ.IMAX) GO TO 840
      IF(VL(I+1,N).GT.VL(I+2,N)) TT(3)=777.
      IF(TT(3).EQ.777.AND.NL.EQ.3) GO TO 835
      IF(LC.EQ.1) GO TO 835

  837 ADJSQ=VL(I+LC,N)*VL(I+LC,N)-VL(I+LC-LF-1,N)*VL(I+LC-LF-1,N)
      ADJSQ=ABS(ADJSQ)
      ADJ=SQRT(ADJSQ)
      TT(NL)=TT(NL)+2.0*(DL(I+LC-LF-1,N)-DL(I+LC-LF-2,N))*ADJ/(VL(I+LC,N
     &)*VL(I+LC-LF-1,N))
      IF(I+2.EQ.IMAX) TT(4)=999.
      IF(I+2.EQ.IMAX) GO TO 840
      IF(VL(I+2,N).GT.VL(I+3,N)) TT(4)=999.
      IF(LC.EQ.2) GO TO 835
      LF=LF+1
      IF(LC.EQ.3.AND.LF.EQ.1) GO TO 837

  840 TT1=TT(1)
      TT2=TT(2)
      TT3=TT(3)
      TT4=TT(4)
      RETURN
```

```
      END
      SUBROUTINE STATS(M,SNDF,SSND)

C *** COMPUTES THE MEAN AND STANDARD DEVIATION *************************

      XM=FLOAT(M)
      ANDF=SNDF/XM
      SSND=SSND/(XM-1.0)
      STD=SQRT(SSND)

      PRINT 894, ANDF,STD
  894 FORMAT (///,T50,'MEAN DIFFERENCE =',F6.2,' *',/,
     &T33,'STANDARD DEVIATION OF DIFFERENCE =',F6.2,' *',//,
     &T38,'* PERCENT OF MEASURED VELOCITY')

      SNDF=0.0
      SSND=0.0

      RETURN
      END
      SUBROUTINE FOROUT (I,J,M,N,IMAX,NL,TT1,TT2,TT3,TT4,SNDF,SSND,VLA,
     &  TT2U,TMIN)

      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
     &             SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
     &            ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
     &,VC(20,20)
      COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
         CHARACTER *60 TITLE

      IF(VA(J,N)) 500,500,400

  400 DIFN=VLA-VA(J,N)
      DIFN=DIFN*100.0/VA(J,N)
      SNDF=SNDF+DIFN
      SSND=SSND+DIFN*DIFN

  500 IF(VA(J,N).EQ.0.0) DIFN=0.0
      IF(TT2U.NE.999) GO TO 200
      IF(TT2.EQ.777.AND.TT3.EQ.777.AND.TT4.EQ.999)
     &PRINT 885, DG(J,N),DS(J,N),VL(I,N),TT1,
     &VLA,VA(J,N)
      IF(TT2.NE.777.AND.TT3.EQ.777.AND.TT4.EQ.999)
     &PRINT 875, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,
     &VLA,VA(J,N)
      IF(TT2.EQ.777.OR.TT3.EQ.777) GO TO 100
      IF(TT2.EQ.999.AND.TT3.EQ.999.AND.TT4.EQ.999)
     &PRINT 885, DG(J,N),DS(J,N),VL(I,N),TT1,
     &VLA,VA(J,N)
      IF(TT2.NE.999.AND.TT3.EQ.999.AND.TT4.EQ.999)
     &PRINT 875, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,
     &VLA,VA(J,N)
      IF(TT2.NE.999.AND.TT3.NE.999.AND.TT4.EQ.999)
     &PRINT 865, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT3,
```

```
     &VLA,VA(J,N)
      IF(TT2.NE.999.AND.TT3.NE.999.AND.TT4.NE.999)
     &PRINT 855, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT3,TT4,
     &VLA,VA(J,N)

 100 CONTINUE
      IF(TT2.EQ.777.AND.TT3.EQ.999.AND.TT4.EQ.999)
     &PRINT 885, DG(J,N),DS(J,N),VL(I,N),TT1,
     &VLA,VA(J,N)
      IF(TT2.EQ.777.AND.TT3.EQ.999.AND.TT4.EQ.999) GO TO 888
      IF(TT2.EQ.777.AND.TT3.NE.777.AND.TT4.EQ.999)
     &PRINT 711, DG(J,N),DS(J,N),VL(I,N),TT1,TT3,
     &VLA,VA(J,N)
      IF(TT2.EQ.777.AND.TT3.NE.777.AND.TT4.NE.999)
     &PRINT 712, DG(J,N),DS(J,N),VL(I,N),TT1,TT3,TT4,
     &VLA,VA(J,N)
      IF(TT2.EQ.777.AND.TT3.EQ.777.AND.TT4.NE.999)
     &PRINT 713, DG(J,N),DS(J,N),VL(I,N),TT1,TT4,
     &VLA,VA(J,N)
      IF(TT2.NE.777.AND.TT3.EQ.777.AND.TT4.NE.999)
     &PRINT 714, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT4,
     &VLA,VA(J,N)
      GO TO 888

 200 CONTINUE
      IF(TT2.EQ.777.OR.TT3.EQ.777) GO TO 300
      IF(TT2.EQ.999.AND.TT3.EQ.999.AND.TT4.EQ.999)
     &PRINT 889, DG(J,N),DS(J,N),VL(I,N),TT1,TT2U,
     &VLA,VA(J,N)
      IF(TT2.NE.999.AND.TT3.EQ.999.AND.TT4.EQ.999)
     &PRINT 878,DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT2U,VLA,VA(J,N)
      IF(TT2.NE.999.AND.TT3.NE.999.AND.TT4.EQ.999)
     &PRINT 868, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT3,TT2U,
     &VLA,VA(J,N)
      IF(TT2.NE.999.AND.TT3.NE.999.AND.TT4.NE.999)
     &PRINT 858, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT3,TT4,TT2U,
     &VLA,VA(J,N)

 300 CONTINUE
      IF(TT2.EQ.777.AND.TT3.EQ.999.AND.TT4.EQ.999)
     &PRINT 889, DG(J,N),DS(J,N),VL(I,N),TT1,TT2U,
     &VLA,VA(J,N)
      IF(TT2.EQ.777.AND.TT3.EQ.999.AND.TT4.EQ.999) GO TO 888
      IF(TT2.NE.777.AND.TT3.EQ.777.AND.TT4.EQ.999)
     &PRINT 878, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT2U,VLA,VA(J,N)
      IF(TT2.EQ.777.AND.TT3.NE.777.AND.TT4.EQ.999)
     &PRINT 721, DG(J,N),DS(J,N),VL(I,N),TT1,TT3,TT2U,
     &VLA,VA(J,N)
      IF(TT2.EQ.777.AND.TT3.NE.777.AND.TT4.NE.999)
     &PRINT 722, DG(J,N),DS(J,N),VL(I,N),TT1,TT3,TT4,TT2U,
     &VLA,VA(J,N)
      IF(TT2.EQ.777.AND.TT3.EQ.777.AND.TT4.NE.999)
     &PRINT 723, DG(J,N),DS(J,N),VL(I,N),TT1,TT4,TT2U,
     &VLA,VA(J,N)
      IF(TT2.NE.777.AND.TT3.EQ.777.AND.TT4.NE.999)
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```
      &PRINT 724, DG(J,N),DS(J,N),VL(1,N),TT1,TT2,TT4,TT20,
      &VLA,VA(J,N)

  888 CONTINUE

  711 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T40,F7.4,T64,2F8.0)
  712 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T40,F7.4,T48,F7.4,
     &T64,2F8.0)
  713 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T48,F7.4,T64,2F7.4)
  714 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T48,F7.4,T64,2F8.0)
  721 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T40,F7.4,T56,F7.4,T64,2F8.0)
  722 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T40,F7.4,T48,
     &F7.4,T56,F7.4,T64,2F8.0)
  723 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T48,F7.4,T56,F7.4,T64,2F8.0)
  724 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,
     &T48,F7.4,T56,F7.4,T64,2F8.0)
  855 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T40,F7.4,
     &T48,F7.4,T64,2F8.0)
  858 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T40,F7.4,
     &T48,F7.4,T56,F7.4,T64,2F8.0)
  865 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T40,F7.4,T64,2F8.0)
  868 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T40,F7.4,
     &T56,F7.4,T64,2F8.0)
  875 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T64,2F8.0)
  878 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T56,F7.4,T64,2F8.0)
  885 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T64,2F8.0)
  889 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T56,F7.4,T64,2F8.0)

      RETURN
      END
      SUBROUTINE SUMARY (JMAX,ISUM)
      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
     &              SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
     &             ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
     &,VC(20,20)
      COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
         CHARACTER *60 TITLE

C *** SETS UP TABLE FOR THREE HOLE SET P AND S WAVE DATA ***************

      CALL ARRANG (JMAX)


      PRINT 100, TITLE
  100 FORMAT ('1',T2,'CROSS HOLE SUMMARY -',A60,///)

      GO TO (500,600,700), ISUM

  500 PRINT 200
  200 FORMAT (T3,'SHOT  GEO B GEC C', 3X,'DIRECT PATH',
     & 2X,'MEASURED ARRIVAL TIMES, SEC ', 6X,'TRUE',
     &T93 ,'APPARENT VELOCITY SUMMARY',
     &/,T3,'DEPTH DEPTH DEPTH', 4X,'DISTANCE',T68,'VELOCITY',
     &T90 ,'P-WAVE', 20X,'S-WAVE',
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      &/,38X,'P-WAVE', 9X,'S-WAVE',
      &T86,'AB',10X,'AC',11X,'AB',10X,'AC',
       &/,T24,'AB    AC',T58,'AB',5X,'AC', 6X,'AB',5X,'AC',
      & 4X,'P-WAVE',1X,'S-WAVE',
      &T82,'MEAS  COMP  MEAS  COMP',3X,'MEAS  COMP  MEAS  COMP',
      &//)

        DO 400 J=1,JMAX
  400 PRINT 410, DS(J,12),DG(J,12),DG(J,13),DP(J,12),DP(J,13),
      & TR(J,12),TR(J,13),TR(J,14),TR(J,15),
      & VL(J,12),VL(J,14),
      & VA(J,12),VC(J,12),VA(J,13),VC(J,13),VA(J,14),VC(J,14),VA(J,15),
      & VC(J,15)
  410 FORMAT (T2,F6.1,   F6.1,   F6.1,1X,F6.1,1X,F6.1,T35,2F7.4,
      &T50,2F7.4, 1X,2F7.0, 2X,4F6.0,1X,4F6.0)
        GO TO 900

  600 CONTINUE

        PRINT 610
  610 FORMAT (
      & 24X,10HHOLE DEPTH, 4X,11HDIRECT PATH, 6X,18HARRIVAL TIMES, SEC,/,
      & 40X, 8HDISTANCE, 6X,6HP-WAVE, 5X, 6HS-WAVE,/,
      &24X,'A     B     C', 5X,'AB    AC', 6X,'AB     AC      AB     AC',
      &//)
        DO 420 J=1,JMAX
  420 PRINT 430, DS(J,12),DG(J,12),DG(J,13),DP(J,12),DP(J,13),
      & TR(J,12),TR(J,13),TR(J,14),TR(J,15)
  430 FORMAT (20X,3F6.1,2F7.0, 1X,2F7.4, 1X,2F7.4)


        PRINT 435
  435 FORMAT(//,23X, 5HDEPTH,                                   14X,
      &26HAPPARENT VELOCITY PROFILES,//,
      & 31X,'COMP  MEAS', 3X,'COMP  MEAS', 3X,'COMP  MEAS', 3X,'COMP  MEA
      &S',//)
        DO 440 J=1,JMAX
  440 PRINT 450, DS(J,12),                                    VC(J,12),
      &VA(J,12),VC(J,13),VA(J,13),VC(J,14),VA(J,14),VC(J,15),VA(J,15)
  450 FORMAT (22X,F6.1,            4(1X,2F6.0))


        PRINT 475
  475 FORMAT (//,31X, 5HDEPTH, 6X,22HTRUE VELOCITY PROFILES,/,
      & 43X, 6HP-WAVE, 8X, 6HS-WAVE,/
      & 41X, 2HAB, 6X, 2HAC, 6X, 2HAB, 6X, 2HAC //)
        DO 480 J=1,JMAX
  480 PRINT 490, DS(J,12),VL(J,12),VL(J,13),VL(J,14),VL(J,15)
  490 FORMAT (30X,F6.1,4F8.0)

  700 CONTINUE

  900 RETURN
        END
        SUBROUTINE ARRANG (JMAX)
```

```
      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
     &             SFGS(50,20),DFGS(50,20),TH(50,20),VA(50,20),DP(50,20)
     &            ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
     &,VC(20,20)
      COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
        CHARACTER *60 TITLE
      J2=0
      J3=0
      J4=0
      J5=0
      I2=1
      I3=1
      I4=1
      I5=1
      DO 450 J=1,JMAX
      N=2
      J2=J2+1
      J3=J3+1
      J4=J4+1
      J5=J5+1
      IF(DS(J,2)) 250,350,250
  250 CONTINUE
      IF(DS(J,2).LT.DS(J3,3)) J3=J3-1
      IF(DS(J,2).LT.DS(J4,4)) J4=J4-1
      IF(DS(J,2).LT.DS(J5,5)) J5=J5-1
  350 CONTINUE
       CONTINUE
      IF(DG(J3,3).LT.DG(J5,5)) DG(J3,3)=DG(J5,5)
      IF(DL(I2,2).LT.DG(J2,2)) I2=I2+1
      IF(DL(I3,3).LT.DG(J2,2)) I3=I3+1
      IF(DL(I4,4).LT.DG(J3,3)) I4=I4+1
      IF(DL(I5,5).LT.DG(J3,3)) I5=I5+1
      IF(DS(J,2)) 390,360,390
  360 CONTINUE
      IF(DL(I4,4).LT.DG(J,4)) I4=I4+1
      DP(J,2)=DP(J,4)
      DS(J,2)=DS(J,4)
      DG(J,2)=DG(J,4)
  390 CONTINUE
      DS(J,12)=DS(J2,2)
      DG(J,12)=DG(J2,2)
```

```
      DG(J,13)=DG(J3,3)
      DP(J,12)=DP(J2,2)
      DP(J,13)=DP(J3,3)
      TR(J,12)=TR(J2,2)
      TR(J,13)=TR(J3,3)
      TR(J,14)=TR(J4,4)
      TR(J,15)=TR(J5,5)
      VL(J,12)=VL(I2,2)
      VL(J,13)=VL(I3,3)
      VL(J,15)=VL(I5,5)
      VL(J,14)=VL(I4,4)
      VA(J,12)=VA(J2,2)
      VC(J,12)=VC(J2,2)
      VA(J,13)=VA(J3,3)
      VC(J,13)=VC(J3,3)
      VA(J,14)=VA(J4,4)
      VC(J,14)=VC(J4,4)
      VA(J,15)=VA(J5,5)
      VC(J,15)=VC(J5,5)
      TR(J2,2)=0.0
      TR(J3,3)=0.0
      TR(J4,4)=0.0
      TR(J5,5)=0.0
      VA(J2,2)=0.0
      VA(J3,3)=0.0
      VA(J4,4)=0.0
      VA(J5,5)=0.0

  450 CONTINUE

      DO 600 N=2,5
      DO 600 J=1,25
      TR(J,N)=0.0
      VA(J,N)=0.0
      VC(J,N)=0.0
      DG(J,N)=0.0
      DS(J,N)=0.0
      SG(J,N)=0.0
      SS(J,N)=0.0
      DP(J,N)=0.0
  600 CONTINUE

      RETURN
      END
      SUBROUTINE CARRYU (M,N,LNIMAX)
      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
     &             SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
     &            ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
     &,VC(20,20)
      COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
       CHARACTER *60 TITLE

      NP=N+1
      NC=N-1
```

```
      DO 100 I=1,LNIMAX
      DL(I,N)=DL(I,NO)
  100 VL(I,N)=VL(I,NO)
      J=0
      JN=1
      JO=1
  200 J=J+1
      IF(DS(JN,N).EQ.0.0.AND.DS(JO,NO).EQ.0.0) GO TO 600
      IF(DS(JN,N)-DS(JO,NO)) 300,400,500

  300 DS(J,NP)=DS(JN,N)
      DG(J,NP)=DG(JN,N)
      JN=JN+1
      GO TO 200

  400 DS(J,NP)=DS(JN,N)
      DG(J,NP)=DS(JN,N)
      JO=JO+1
      JN=JN+1
      GO TO 200

  500 DS(J,NP)=DS(JO,NO)
      DG(J,NP)=DG(JO,NO)

      JO=JO+1
      GO TO 200

  600 M=J-1
      DO 700 JJ=1,M
  700 DS(JJ,N)=DS(JJ,NP)
      RETURN
      END
      SUBROUTINE SUMTWO (M,N)

      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
     &              SFGS(50,20),DFGS(50,20),TH(50,20),VA(50,20),DF(50,20)
     &             ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
     &,VC(20,20)
      COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
        CHARACTER *60 TITLE

      PRINT 90
      PRINT 100
  100 FORMAT (/,30X, 7HTABLE 3,///
     & 25X, 6H'REAL', 5X,17HAPPARENT VELOCITY, 2X,12H'SUPPOSEDLY',/
     &15X, 5HDEPTH, 2X,        13HTRUE VELOCITY, 8X, 3HFOR,
     & 9X,               13HTRUE VELOCITY,/
     &37X,           14H 35 M SPACING ,/
     &16X, 4H( M), 6X, 5H(MPS),11X, 5H(MPS),12X, 5H(MPS),//)
C    337X,           14H100 FT SPACING,/
C    416X, 4H(FT), 6X, 5H(FPS),11X, 5H(FPS),12X, 5H(FPS),//)

      I1=1
      I2=1
```

```
      NP=N+1
      DO 200 J=1,M
      IF(DS(J,N).GT.DL(I1,N)) I1=I1+1
      IF(DS(J,N).GT.DL(I2,NP)) I2=I2+1
  200 PRINT 110, DS(J,N),VL(I1,N),VA(J,NP),VL(I2,NP)
      PRINT 250
  250 FORMAT (//, 7X,65HNOTE - THE 'SUPPOSEDLY' TRUE VELOCITY PROFILE IS
     & A PLAUSIBLE, BUT,
     &             /,14X,    'ERRONEOUS, INTERPRETATION OF THE GIVEN APPA
     &RENT VELOCITY PROFILE.')

   90 FORMAT (1H1)
  110 FORMAT (15X,F5.1, 4X,F7.0, 9X, F7.0, 9X, F7.0)
  310 FORMAT ( 5X, F5.1, 4X, F7.0, 4X, 2F7.0, 2X, 2F7.0)

      PRINT 90
      PRINT 300
  300 FORMAT (/,20X, 7HTABLE 5,///
     & 5X, 5HDEPTH, 2X,13HTRUE VELOCITY, 2X,25HAPPARENT VELOCITIES (MPS)
     &  ,/,6X, 4H( M), 6X, 5H(MPS), 9X, 7H 0-7 M , 8X, 8H 0-35 M ,/
C    1 5X, 5HDEPTH, 2X,13HTRUE VELOCITY, 2X,25HAPPARENT VELOCITIES (FPS)
C    2  ,/,6X, 4H(FT), 6X, 5H(FPS), 9X, 7H0-20 FT, 8X, 8H0-100 FT,/
     & 27X, 4HCOMP, 3X, 4HMEAS, 5X, 4HCOMP, 3X, 4HMEAS,//)

      I=1
      DO 400 J=1,M
      IF(DS(J,N).GT.DL(I,N)) I=I+1
  400 PRINT 310, DS(J,N),VL(I,N),VC(J,N),VA(J,N),VA(J,N+1),VA(J,N+1)

      RETURN
      END
      SUBROUTINE TABDUM(M,IMAX)

      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
     &               SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DM(50,20)
     &               ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
     &,VC(20,20)
      COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
         CHARACTER *60 TITLE

C     PRINT 130

      PRINT 502
  502 FORMAT (15X,47HAPPARENT VELOCITY AS A FUNCTION OF HOLE SPACING///,
     &3X,26HDEPTH      TRUE   INTERFACE,11X,25HAPPARENT VELOCITIES FOR,/,
     &11X,16HVELOCITY   DEPTH,16X,16HHOLE SPACINGS OF,/,
     &12X,7HPROFILE,13X,38H  7 M     14 M     21 M     28 M     35 M ,//)
C    312X,7HPROFILE,13X,38H 20 FT    40 FT    60 FT    80 FT  100 FT,//)

      I=1
      J=0
  200 J=J+1
      IF(J.GT.M) GO TO 600
      IF(DL(I,2).LT.DS(J,2)) GO TO 400
```

```
 300 PRINT 110, DS(J,2),VL(I,2),VA(J,2),VA(J,3),VA(J,4),VA(J,5),VA(J,6)
     PUNCH 110, DS(J,2),VL(I,2),VA(J,2),VA(J,3),VA(J,4),VA(J,5),VA(J,6)
     IF(J.EQ.M) GO TO 600
     GO TO 200
 400 PRINT 120, DL(I,2)
     PUNCH 120, DL(I,2)
     I=I+1
     GO TO 300
 600 IF(I.LT.IMAX) PRINT 140, DL(I,2),VL(I+1,2)

 100 FORMAT (6(20A4))
 101 FORMAT (6(13A6,A2,/))
 110 FORMAT (2X,F6.1,3X,F7.0,12X,5F8.0)
 120 FORMAT (21X,F6.1)
 130 FORMAT (1H1)
 140 FORMAT (21X,F6.1,/,11X,F7.0)

     RETURN

     END
     SUBROUTINE OPUNCH (M,N,IMAX,DIST,AZIM)
     COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
    &             SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DF(50,20)
    &            ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
     COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
    &,VC(20,20)
     COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
        CHARACTER *60 TITLE

     IOP1=2
     IOP2=0
      PUNCH 100,TITLE
 100 FORMAT(A60)
     PUNCH 110, IOP1,N,IOP2,M,DIST,AZIM,VFIRST,VLAST,DLLAST,IMAX
     PUNCH 110, IOP1,N,IOP2,M,DIST
 110 FORMAT (4I5,4F10.1,F5.0,I5,F5.0)
     DO 200 J=1,M
 200 PUNCH 120, SZ(J),SX(J),SY(J),GZ(J),GX(J),GY(J),VC(J,N)
 120 FORMAT (6F10.2,10X,F10.0)
     PUNCH 130, (VL(I,N),I=1,IMAX)
     PUNCH 130, (DL(I,N),I=1,IMAX-1)
 130 FORMAT ((8F10.1))

     RETURN
     END
```

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Analytical and data processing techniques for interpretation of geophysical survey data with special application to cavity detection / by Dwain K. Butler ... [et al.] (Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. ; available from NTIS, 1982.

233 p. in various pagings : ill. ; 27 cm. -- (Miscellaneous paper ; GL-82-16)

Cover title.

"September 1982."

Final report.

"Prepared for Office, Chief of Engineers, U.S. Army under Project 4A161102AT22, Task A0, Work Unit 002."

Bibliography: p. 127-130.

1. Automatic data processing. 2. Computer programs. 3. Geophysical research. I. Butler, Dwain K. II. United States. Army. Corps of Engineers. Office

Analytical and data processing techniques : ... 1982.
(Card 2)

of the Chief of Engineers. III. U.S. Army Engineer Waterways Experiment Station. Geotechnical Laboratory. IV. Series: Miscellaneous paper (U.S. Army Engineer Waterways Experiment Station) ; GL-82-16.

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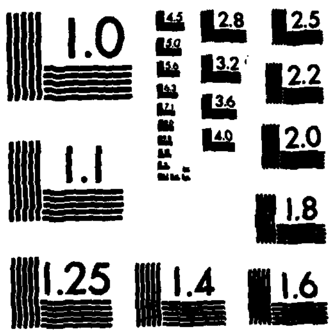

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IN REPLY REFER TO: WESGH

10 December 1982

AD-A121196

Errata Sheet

No. 1

ANALYTICAL AND DATA PROCESSING TECHNIQUES FOR INTERPRETATION OF GEOPHYSICAL SURVEY DATA WITH SPECIAL APPLICATION TO CAVITY DETECTION

Miscellaneous Paper GL-82-16

September 1982

1. Page 14, paragraph 7, line 7, and Equation 1 (line 8), should be changed to read:

   calculate an apparent resistivity ρ_A

$$\rho_A = K_G\left(\frac{\Delta V}{I}\right) \tag{1}$$

2. Page 14, paragraph 7, line 11, should be changed to read:

   $K_G = 2\pi a$; and for the Schlumberger array $K_G = \pi s\left[(L/s)^2 - (1/4)\right]$,

3. Page 14, paragraph 7, line 17, should be changed to read:

   $\pi rn(n^2 - 1)$, where $r = C_1C_2 = P_1P_2$ and $C_1P_1 = C_2P_2 = nr$.

4. Page 68, paragraph 66, line 13, should be changed to read:

   and Equation 4 can be written

5. Page 72, paragraph 70, line 5 on this page, should be changed to read:

   where $f^D(x)$ denotes the discrete profile data set. That is, two

6. Page 93, paragraph 98, line 16 on this page, should be changed to read:

   gradient model in Figure 49a, could now be determined by using TALGRAD

END